Nucleon Spin Structure

Sebastian Kuhn

Old Dominion University

Overview

- Introduction
- What do we measure?
- What do we want to learn? - QCD, effective theories and models
- Status from SLAC, CERN, HERA
- The JLab Program with Hall A…
- … and RSS
- Experiments with CLAS - EG1 and EG4
- Outlook: Future Experiments at JLab

GDH, ChPT

Duality

OPE, twist >2

Orbital Angular Momentum

Resonance

Structure

Bjorken Sum Rule

Δq, ΔG,

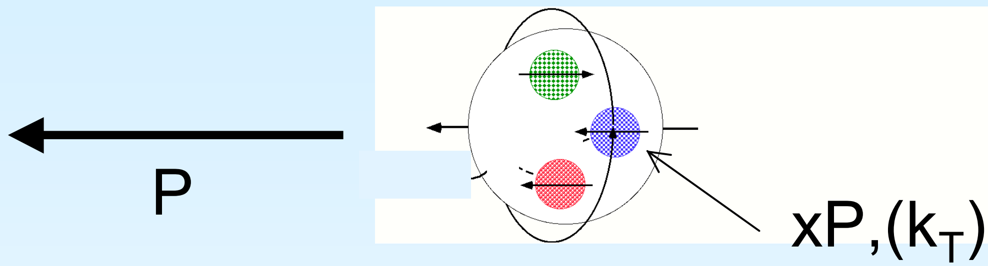
$x \to 1$

TMD

PDFs

DVCS

Quark-Parton Structure of the Nucleon



(analog for transverse nucleon spin)

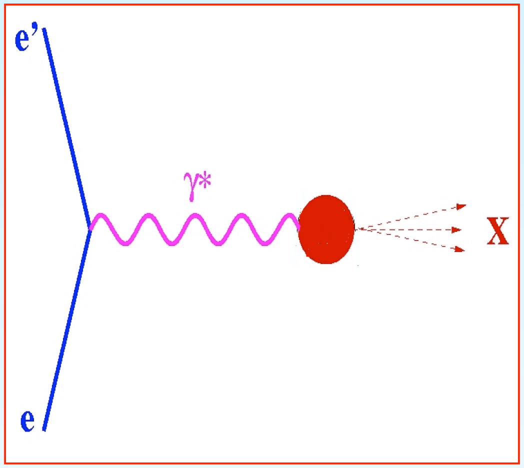
q(x) $\sim \left\langle P,s \middle| \bar{q}\gamma^{\mu} q \middle| P,s \right\rangle$

Δq(x) $= q\Uparrow\uparrow(x) - q\Uparrow\downarrow(x) + \bar{q}\Uparrow\uparrow(x) - \bar{q}\Uparrow\downarrow(x) \sim \left\langle P,s \middle| \bar{q}\gamma^{\mu}\gamma^{5} q \middle| P,s \right\rangle$

"axial charge", similarly G(x) and ΔG(x) for gluons

Spin Sum Rule: $$S_p = \frac{1}{2} = \frac{1}{2}\underbrace{\sum_q \Delta q}_{\Delta\Sigma} + \Delta G + L_q + L_G$$

Measuring Δq

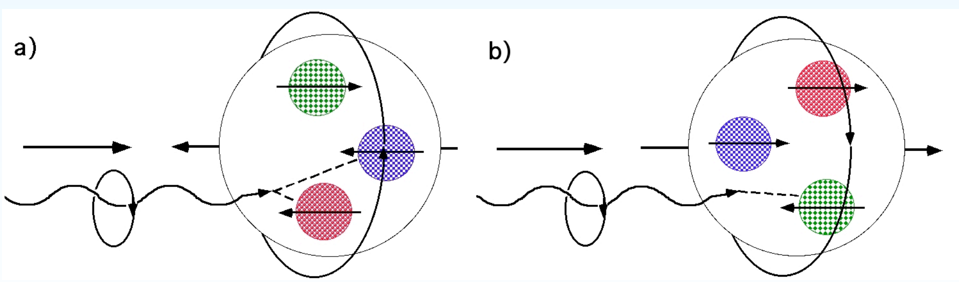


DIS: large energy transfer ν,

4-momentum transfer $Q^2 = \mathbf{q}^2 - \nu^2$,

final state mass $W^2 = M^2 + 2M\nu - Q^2$,

but finite $x = Q^2 / 2M\nu$



longitudinally polarized lepton -> transfer polarization partially to virtual photon

Probes aligned quarks $q \Uparrow\uparrow$

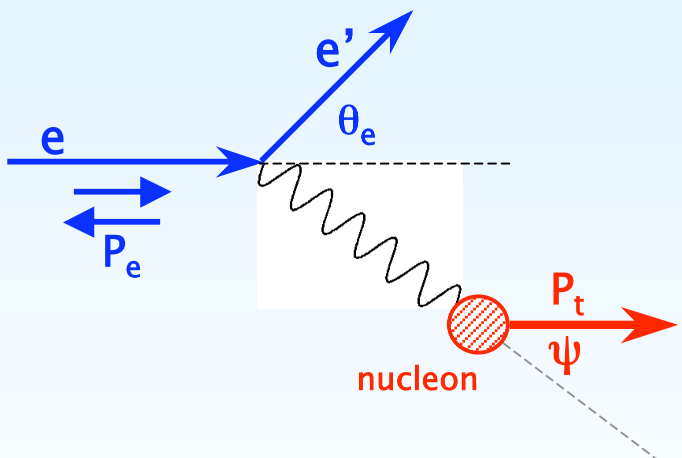
Probes anti-aligned quarks $q \Uparrow\downarrow$

contribution from q weighted by e_q^2

Virtual Photon Asymmetries - Measurement

$$\frac{d\sigma}{dE'\,d\Omega} = \Gamma_v\left[\sigma_T + \varepsilon\sigma_L + P_e P_t\left(\sqrt{1-\varepsilon^2}A_1\sigma_T\cos\psi + \sqrt{2\varepsilon(1-\varepsilon)}A_2\sigma_T\sin\psi\right)\right]$$

$$\mathbf{A_1} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_T} \qquad \mathbf{A_2} = \frac{\sigma_{LT'}}{\sigma_T}$$



the asymmetries A_1 and A_2 can be extracted by varying the *direction of the nucleon polarization*

$$A^{\parallel} = D(A_1 + \eta A_2)$$
$$A^{\perp} = d(A_1 + \zeta A_2)$$

[where D, η, d, ζ are functions of Q^2, E′, E, R, e.g.:

$$D = \frac{1 - \varepsilon E'/E}{1 + \varepsilon R}$$

$$\eta = \frac{\varepsilon\sqrt{Q^2}}{E - \varepsilon E'} \qquad R = \frac{\sigma_L}{\sigma_T}\quad]$$

or by varying the *beam energy* at fixed Q^2, ν

$$A_1 \approx \frac{\sum_i e_i^2 \Delta q_i(x)}{\sum_i e_i^2 q_i(x)}$$

Spin Structure Functions

$$\frac{d\sigma}{dE'd\Omega}\downarrow\Uparrow-\frac{d\sigma}{dE'd\Omega}\uparrow\Uparrow=\frac{4\alpha^2E'}{M\nu Q^2E}\left[\left(E+E'\cos\theta\right)\mathbf{g_1}-2xM\mathbf{g_2}\right]$$

Unpolarized: $F_1(x,Q^2)$ and $F_2(x, Q^2)$

Polarized: $g_1(x,Q^2)$ and $g_2(x, Q^2)$

Parton model:

$$F_1(x)=\tfrac{1}{2}\sum_i e_i^2 q_i(x)\ \text{ and } F_2(x)=2xF_1(x)$$

$$g_1(x)=\tfrac{1}{2}\sum_i e_i^2 \Delta q_i(x)\ \text{ and } g_2(x)=0$$

$i =$ quark flavor

$e_i =$ quark charge

the structure functions $\mathbf{g_1}$ and $\mathbf{g_2}$ are linear combinations of $\mathbf{A_1}$ and $\mathbf{A_2}$

$$g_1(x,Q^2)=\frac{\tau}{1+\tau}(A_1+\frac{1}{\sqrt{\tau}}A_2)F_1$$

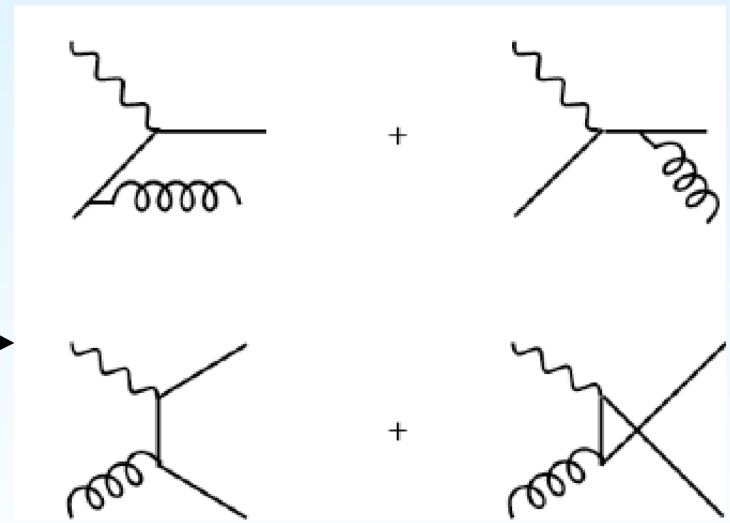
$$g_2(x,Q^2)=\frac{\tau}{1+\tau}(\sqrt{\tau}A_2-A_1)F_1$$

$$\tau=\frac{\nu^2}{Q^2}$$

Parton Distribution Functions and NLO pQCD

Two effects modify simple parton picture:

1) (Gluon) radiative corrections change elementary cross section



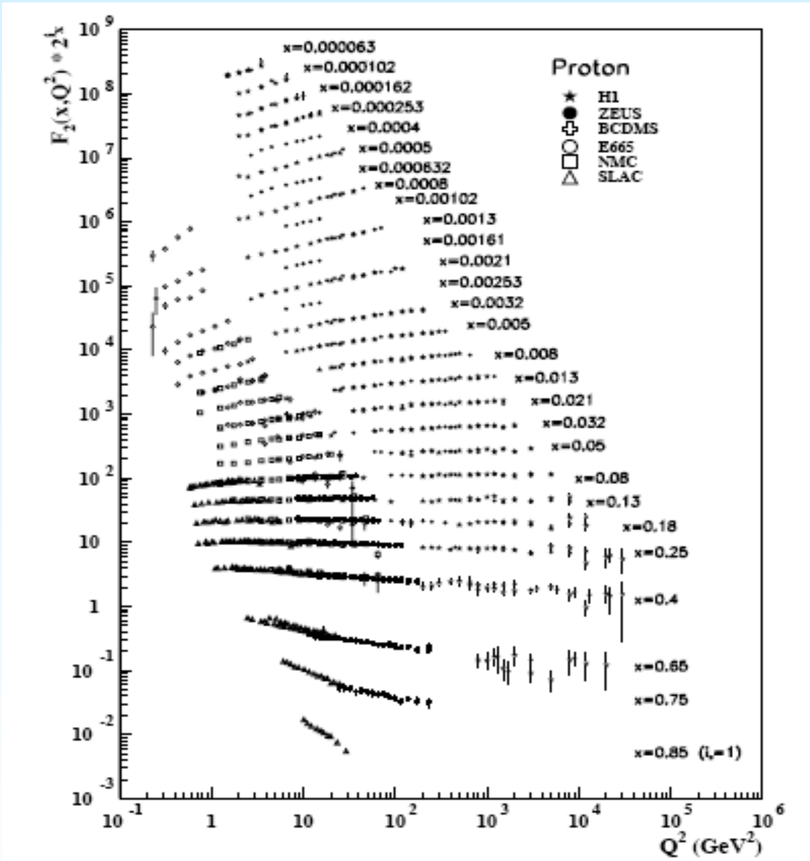
$$g_1(x,Q^2)_{pQCD}=\frac{1}{2}\sum_q^{N_f} e_q^2[(\Delta q+\Delta\bar{q})\otimes(1+\frac{\alpha_s(Q^2)}{2\pi}\delta C_q)+\frac{\alpha_s(Q^2)}{2\pi}\Delta G\otimes\frac{\delta C_G}{N_f}]$$

$\delta C_q, \delta C_G - Wilson$ coefficient functions

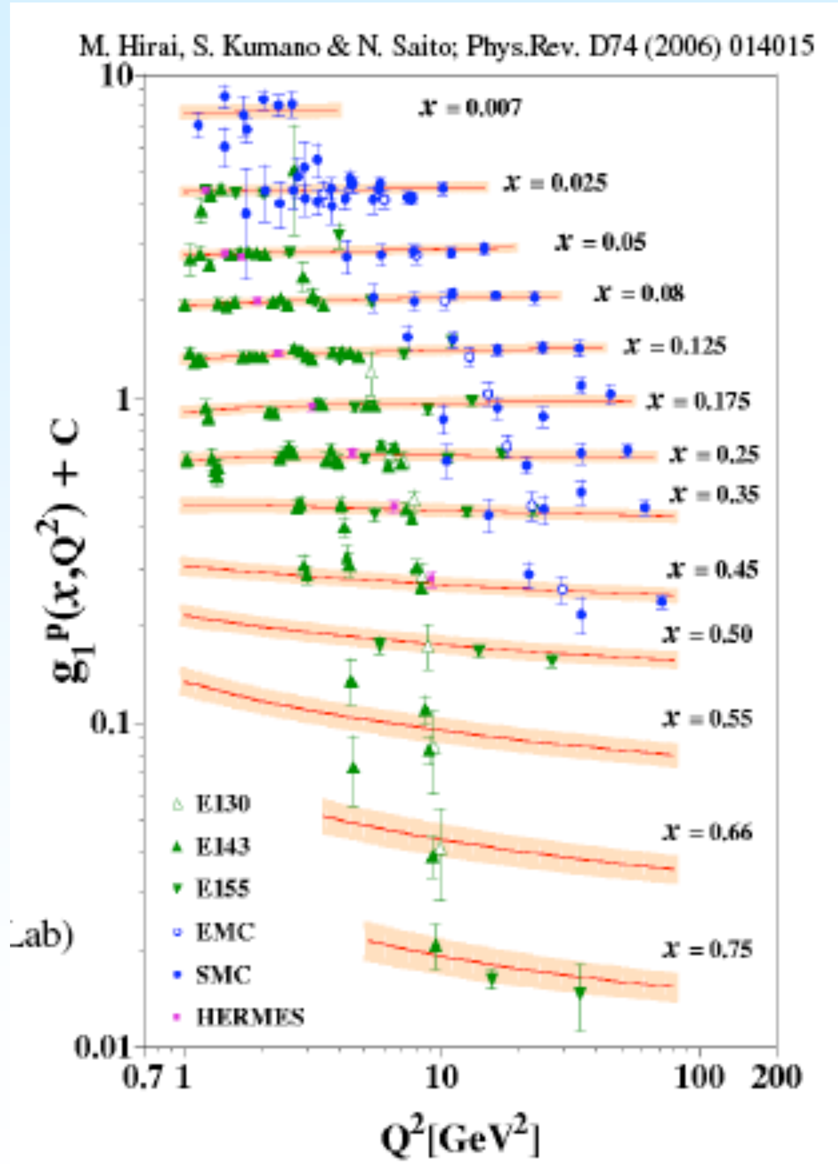
2) pQCD evolution makes PDFs Q^2-dependent

→ we can extract information on the gluon from DIS

Unpolarized SF



Polarized SF



Q^2-evolution governed by Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations. Simultaneous fit to all inclusive data -> quark (and even Gluon) PDFs at some fixed scale

Moments of spin structure functions

- Related to matrix elements of local operators - in principle accessible to lattice QCD calculations
- Sum rules relate moments to the total spin carried by quarks in the nucleon and to axial vector coupling g_A of the nucleon

1st moment

$$\Gamma_1^{\,p}\left(Q^2\right) = \int_0^1 g_1^{\,p}\left(x,Q^2\right)dx = \frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right)$$

$$= \left(\frac{g_A^{(3)}}{12} + \frac{g_A^{(8)}}{36}\right)C_{NS}\left(Q^2\right) + \frac{\Delta\Sigma}{9}C_S\left(Q^2\right)$$

$$\boxed{\begin{aligned} g_A^{(3)} &= \Delta u - \Delta d \ (\text{n} \rightarrow \text{p axial form factor}) \\ g_A^{(8)} &= \Delta u + \Delta d - 2\Delta s \ (\text{hyperon decay}) \end{aligned}}$$

non-singlet and singlet Wilson Coeff.

$$C_{NS} = 1 - \frac{\alpha_s}{\pi} - 3.583333\left(\frac{\alpha_s}{\pi}\right)^2 + \ldots \qquad C_S = 1 - \frac{1}{3}\frac{\alpha_s}{\pi} - 0.54959\left(\frac{\alpha_s}{\pi}\right)^2 - \ldots$$

Bjorken Sum Rule (fundamental)

$$\Gamma_1^{p-n} = \int g_1^p\,dx - \int g_1^n\,dx = \frac{g_A^{(3)}}{6}C_{NS}$$

Higher Twist contributions

Further modification of the first moment of g_1 due to quark-gluon and quark-quark correlations:

$$\Gamma_1(Q^2) = \mu_2(\ln Q^2) + \frac{\mu_4(\ln Q^2)}{Q^2} + \cdots; \qquad \mu_4 = \frac{M^2}{9}\left(a_2 + 4d_2 + 4f_2\right)$$

twist-2
targ. mass

$$d_2\left(Q^2\right) = \int_0^1 x^2\left[2g_1\left(x,Q^2\right) + 3g_2\left(x,Q^2\right)\right]dx$$

twist-3

$$f_2(Q^2)\ M^2 S^\mu \ = \ \frac{1}{2}\sum_q e_q^2\ \langle N|g\ \bar{\psi}_q\ \widetilde{G}^{\mu\nu}\gamma_\nu\ \psi_q|N\rangle$$

Twist-4; related to the “Color-polarizability” of the nucleon - accessible through Q^2-dependence of $\Gamma_1(Q^2)$

The 2nd SSF g_2

In parton model, $g_2 = 0$ for massless quarks

In DIS, Wandura-Wilczek (no higher twist):

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{g_1(x,Q^2)}{y} dy$$

Higher Twist

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \overline{g}_2(x,Q^2)$$

Burkardt-Cottingham Sum Rule:

$$\Gamma_2(Q^2) = \int_0^1 g_2(x,Q^2)dx = 0$$

expected to be valid at all Q^2

Valence Region and moderate Q^2: SFs for $x \rightarrow 1$

- SU(6)-symmetric wave function of the proton in the "naïve" quark model:

$$|p\uparrow\rangle = \frac{1}{\sqrt{18}}\left(3u\uparrow[ud]_{S=0} + u\uparrow[ud]_{S=1} - \sqrt{2}u\downarrow[ud]_{S=1} - \sqrt{2}d\uparrow[uu]_{S=1} - 2d\downarrow[uu]_{S=1}\right)$$

- In this model: d/u = 1/2, Δu/u = 2/3, Δd/d = -1/3 for all $x \Rightarrow$

$$\sum_q \Delta q = 1 \quad \Rightarrow \quad S_p = \frac{1}{2}\sum_q \Delta q = \frac{1}{2}\Delta\Sigma; \quad g_A^{(3)} = \Delta u - \Delta d = 5/3; \quad g_A^{(8)} = \Delta u + \Delta d - 2\Delta s = 1$$

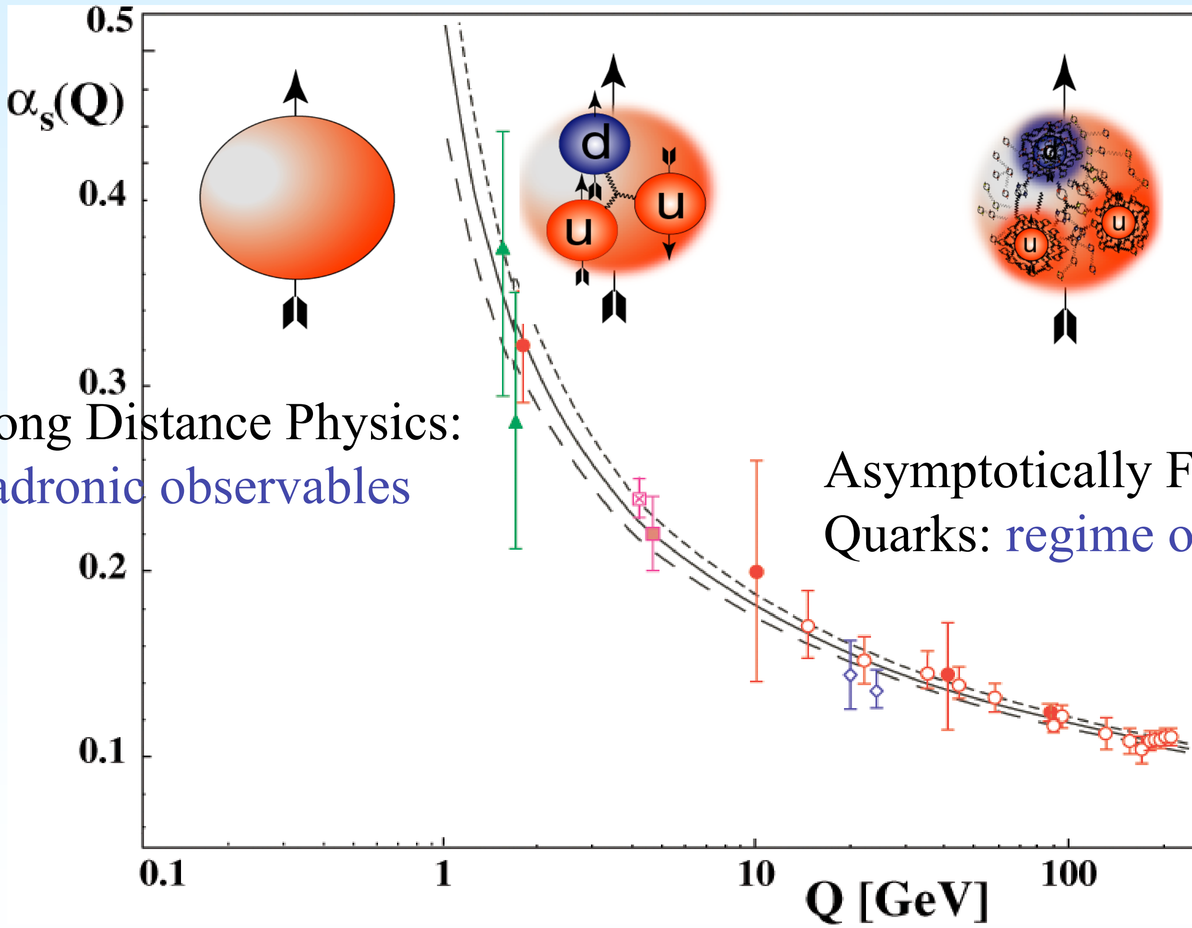
- Relativistic Correction: lower component reduces axial charge, adds to orbital angular momentum (p-wave) ⇒

$$\sum_q \Delta q = \Delta\Sigma \approx 60\%; \quad g_A^{(3)} = \Delta u - \Delta d \approx 1.26; \quad g_A^{(8)} = \Delta u + \Delta d - 2\Delta s \approx 0.6$$

- Hyperfine structure effect: S=1 suppressed => d/u = 0, Δu/u = 1, Δd/d = -1/3 for $x \rightarrow 1$ => $A_{1p} = 1$, $A_{1n} = 1$, $A_{1D} = 1$

- pQCD: helicity conservation (q↑↑p) => d/u =2/(9+1) = 1/5, Δu/u = 1, Δd/d = 1 for $x \rightarrow 1$

Duality



Long Distance Physics:
hadronic observables

Asymptotically Free
Quarks: regime of pQCD

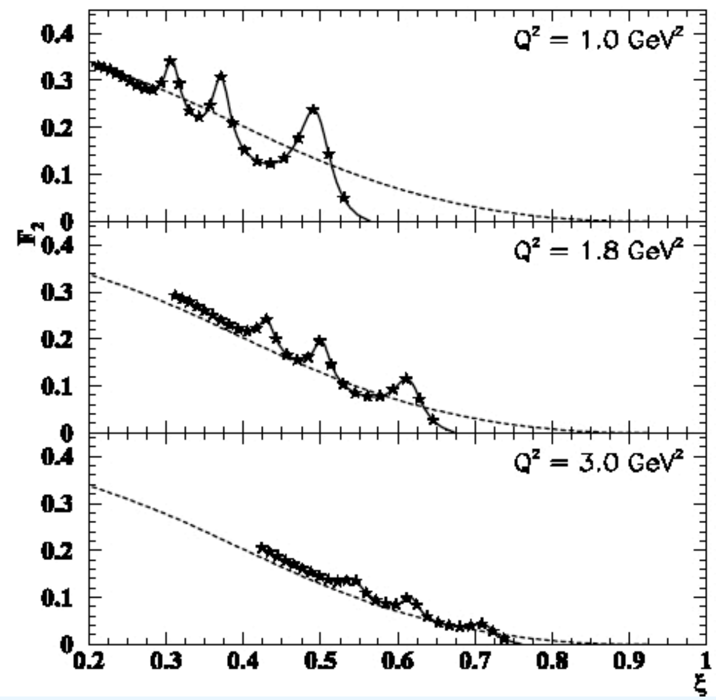
κ

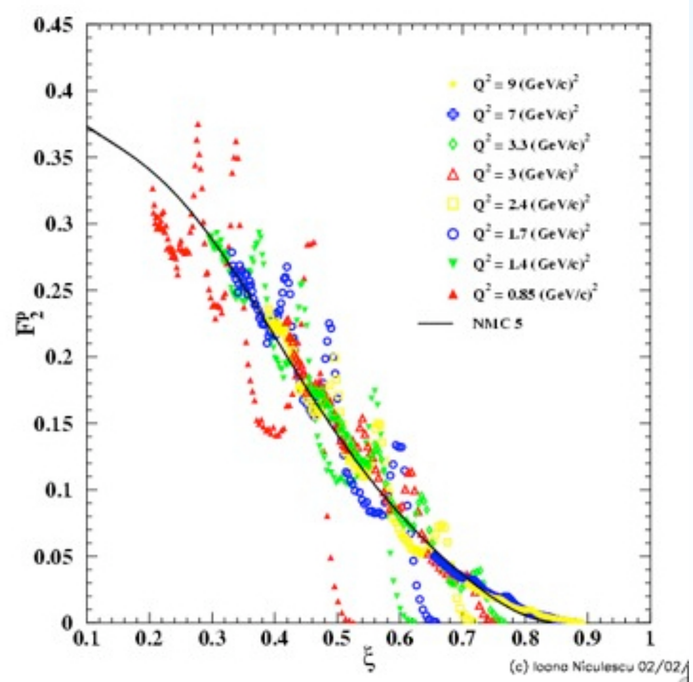
g_A

- Nucleon resonances at low Q^2 average to the scaling curve measured in DIS
  - Bloom and Gilman, PRL **25**, 1140 (1970); PRD **4**, 2901 (1971)
- Observed with high precision in the unpolarized F_2^p structure function in Hall C, Jlab
  - I. Niculescu *et al.,* PRL **85**, 1182, 1186 (2000)
- Local duality also observed (*i.e.,* average over a smaller range in W)
- Related to the absence of higher twist strength in structure function moments
- Also valid for spin structure functions? Not so obvious - can change in sign:

$$A_1^{DIS}(x \to 1) \to 1$$

$$A_1^{\Delta}(\text{low } Q^2) \approx -\frac{1}{2} \quad \left(\sigma_{\frac{3}{2}} > \sigma_{\frac{1}{2}}\right)$$





The Limit $Q^2 \rightarrow 0$: **GDH Sum Rule**

$$I_{GDH} = \frac{M^2}{8\alpha\pi^2}\int_{thr}^{\infty}\left(\sigma_{1/2}-\sigma_{3/2}\right)\frac{d\nu}{\nu} = -\frac{1}{4}\kappa^2$$

- relates the difference of the photo-absorption cross section for helicity 1/2 and 3/2 to the nucleon magnetic moment, i.e. a connection between dynamic and static properties

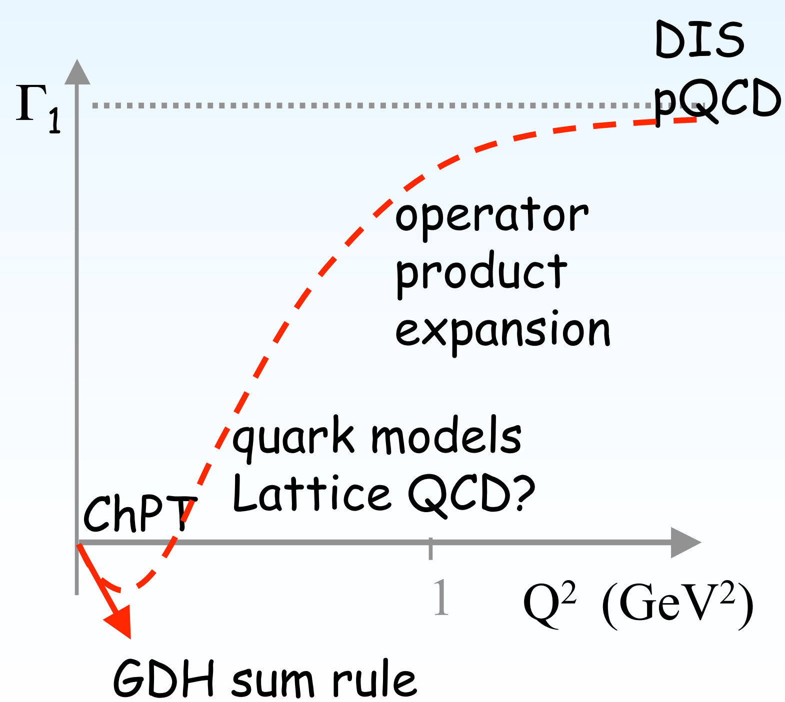
- based on very general principles, as gauge invariance, dispersion relation, low energy theorem

- at finite Q^2 can be related to the integral of the spin structure function g_1

$$\Gamma_1 = \int g_1\left(x,Q^2\right)dx \xrightarrow[Q^2 \to 0]{} \frac{Q^2}{2M^2} I_{GDH}$$

- strong variation of nucleon spin properties as a function of Q^2

- Q^2-dependence described by Chiral Perturbation Theory (χPT) at low Q^2



The Limit $Q^2 \to 0$: Spin Polarizability

$$\int_{thr}^{\infty} (\sigma_{1/2} - \sigma_{3/2}) \frac{d\nu}{\nu^3} = 4\pi^2 \gamma_0$$

- γ_0 measures the response ("stiffness") of the nucleon spin against electromagnetic deformations along the spin axis

- Follows from same dispersion relation and low energy theorem (limit of forward Compton scattering) as GDH sum rule

- can also be extended to finite Q^2:

$$\Gamma_3^N = \int x^2 g_1^N(x,Q^2)\, dx \xrightarrow[Q^2 \to 0]{} \frac{Q^6}{16\alpha M^2} \gamma_0^N$$

- much more sensitive to low-energy (high x) part of the integral -> ideal for Jlab

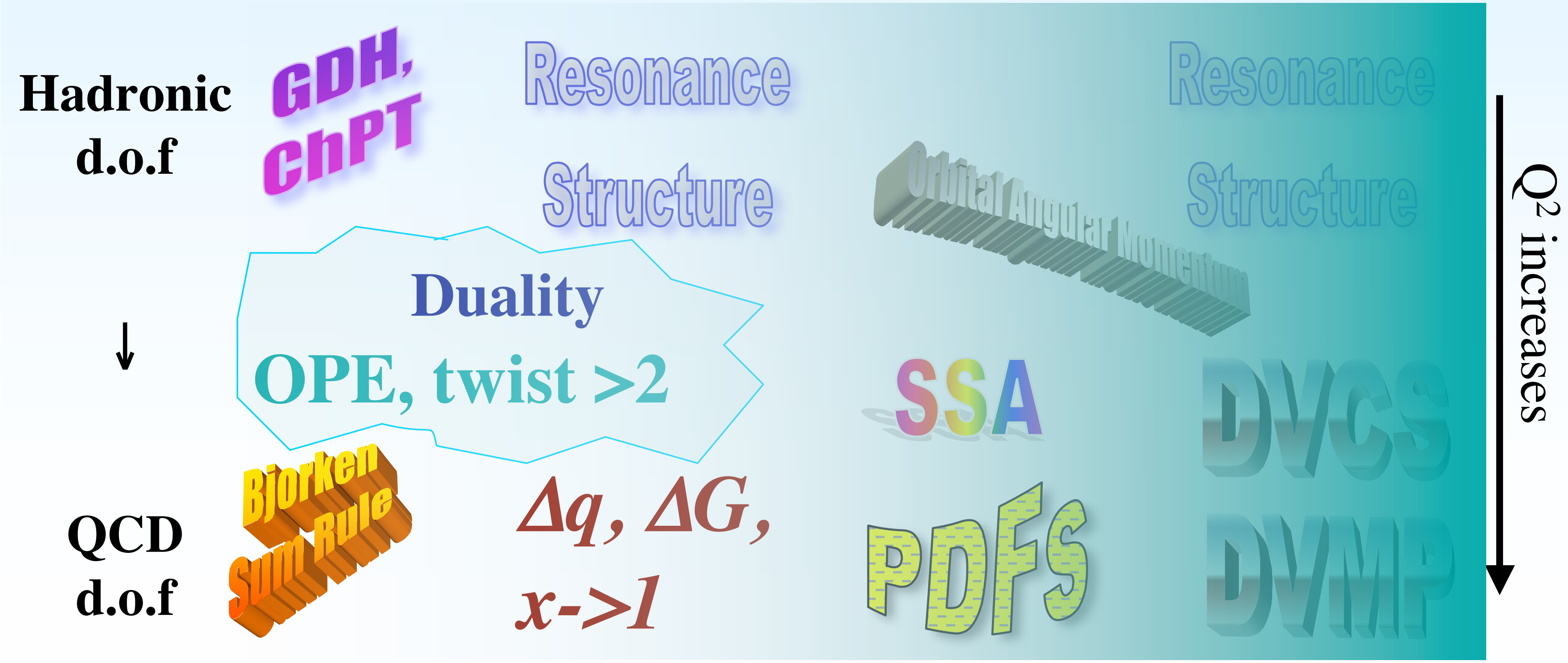
- plus other polarizabilities: δ_{LT}

- $\Rightarrow$ Chiral Perturbation Theory should be able to predict $\gamma_0(Q^2)$, $\delta_{LT}(Q^2)$ and **b** in $\Gamma_1(Q^2) = -\frac{\kappa^2}{8M^2} Q^2 + \boxed{b} Q^4 \ldots$

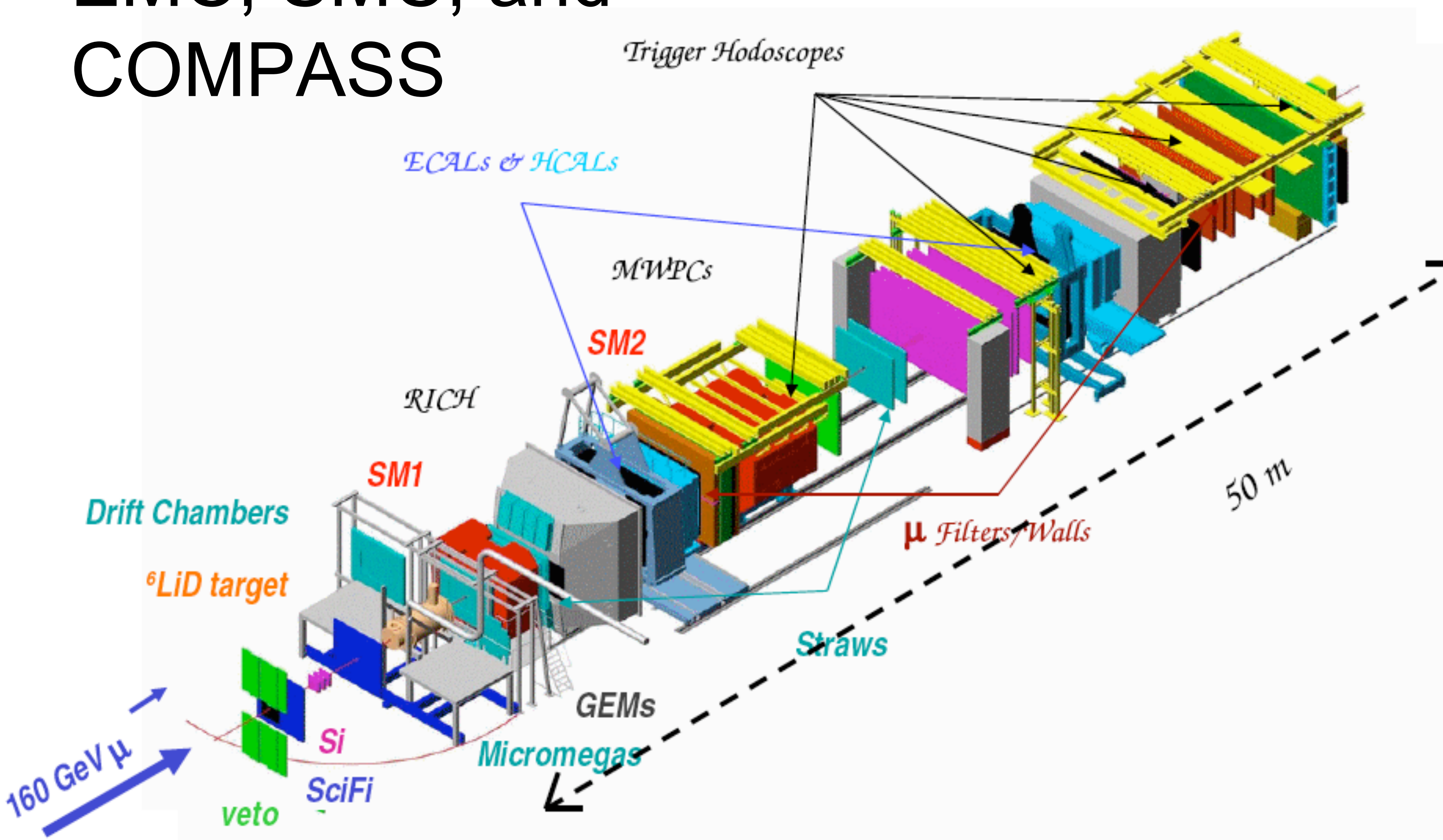
The Landscape of Nucleon Spin

Inclusive → **Exclusive**

Moments	SSFs g_1, g_2, A_1	SIDIS h_1, TMD	Fully recon-structed FS

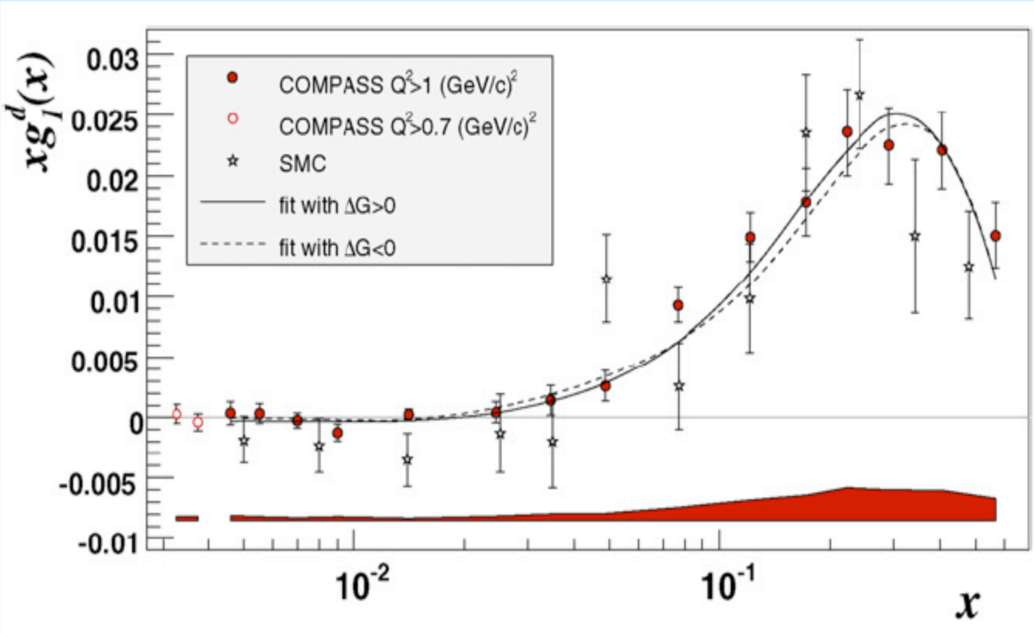


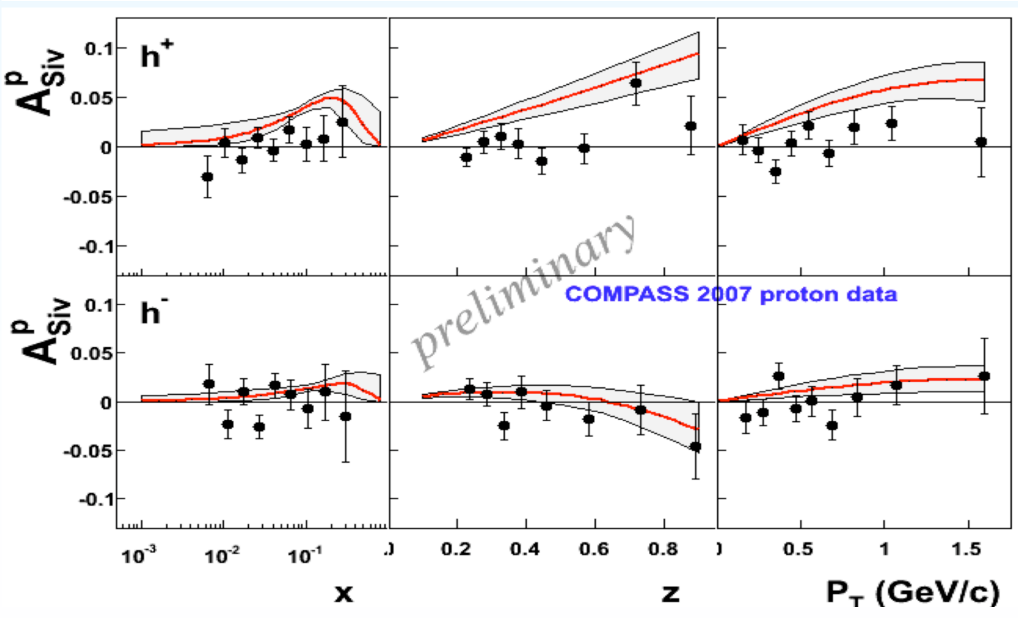
Experiments at CERN: EMC, SMC, and COMPASS

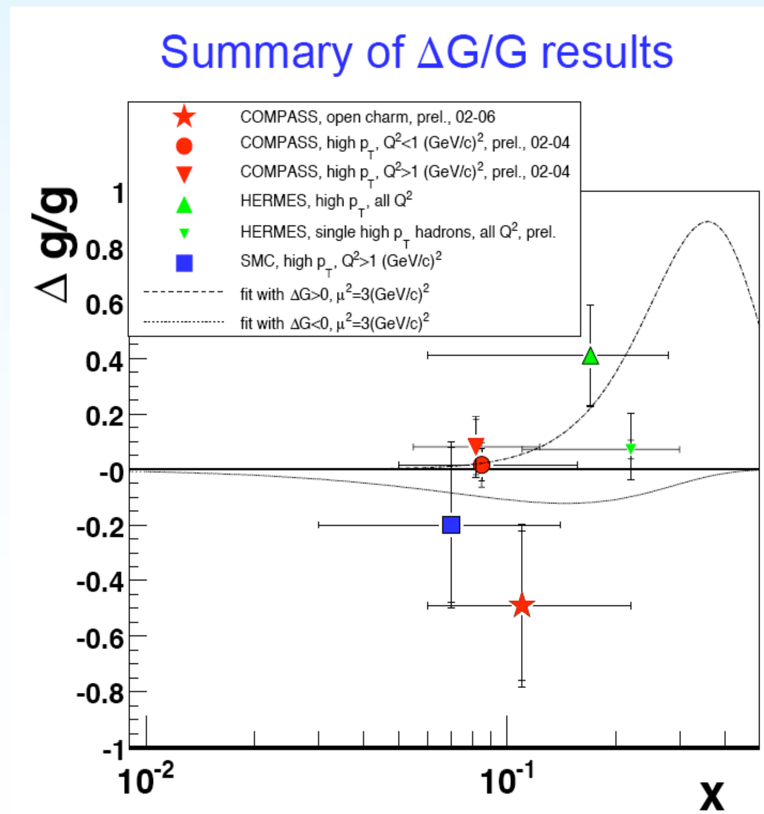


Important Results:

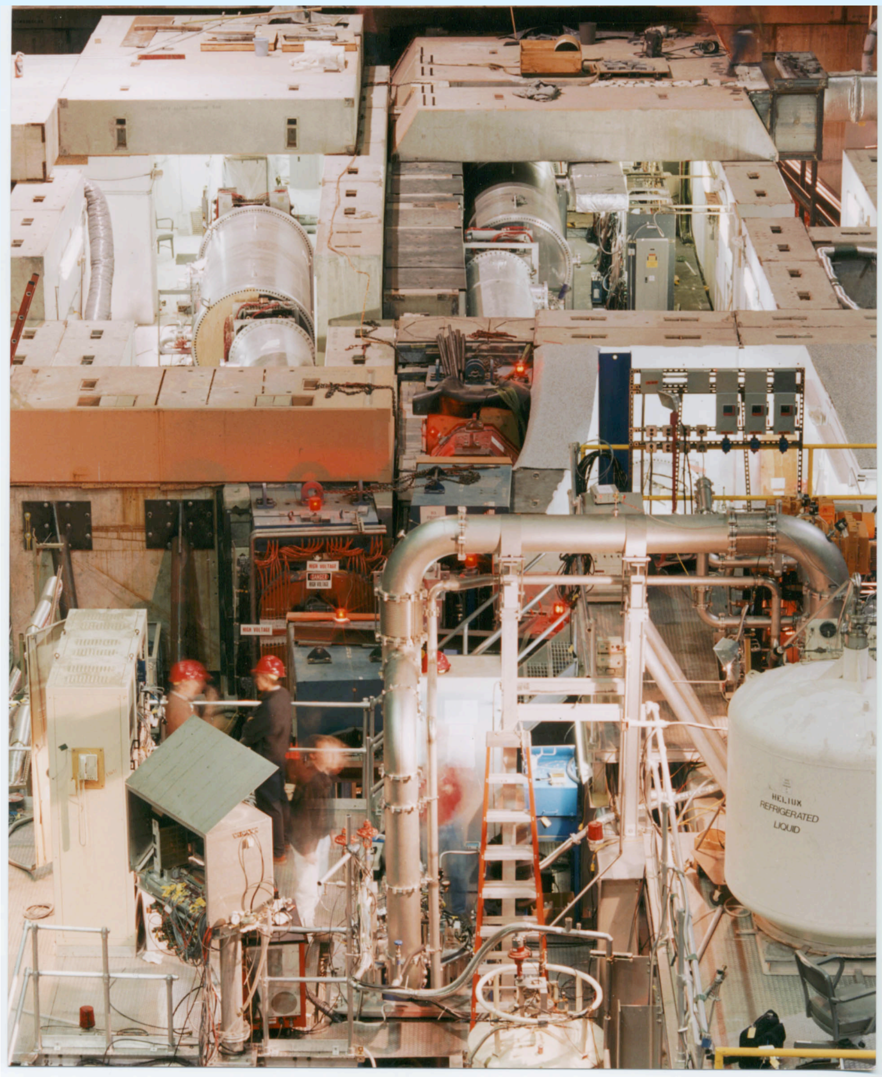
- EMC: Found “spin crisis”
- SMC: First measurement on deuteron; low x / high Q2; Bjorken Sum Rule; semi-inclusive data
- COMPASS: Extended kinematic range and precision -> higher precision NLO fits; direct measurements of gluon polarization (high p_T and open charm); Sivers asymmetries etc…







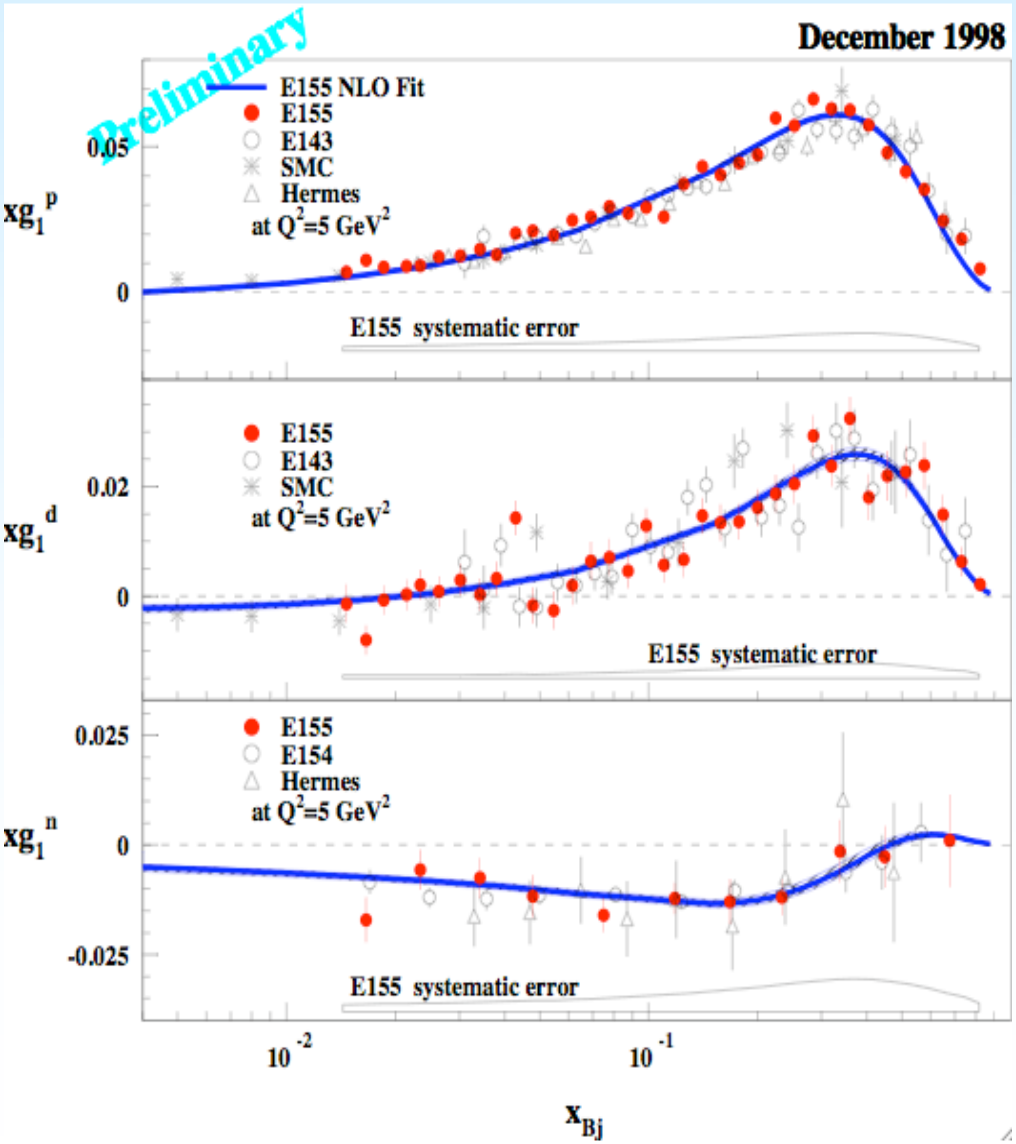
Experiments at SLAC: E80, E130, E142, E143, E154, E155, E155x

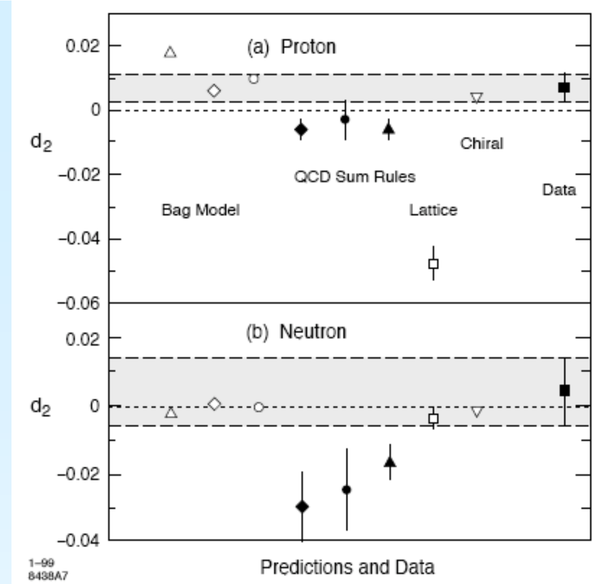


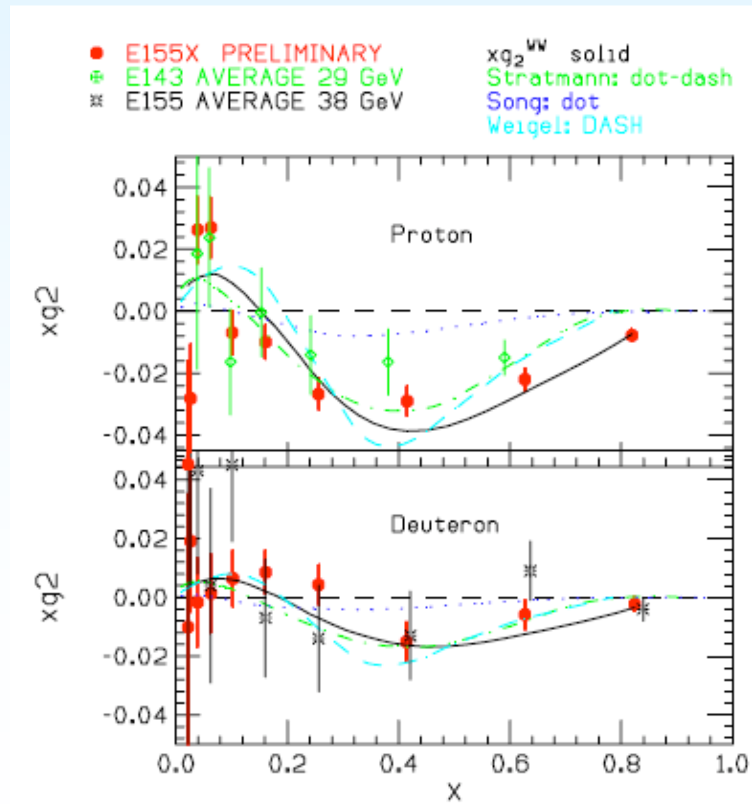
- Polarized electron beam from 9.7 to 50 GeV
- Polarized ^{3}He gas targets (n) and solid $^{15}NH_3$, $^{15}ND_3$ and LiD targets (p,d); longitudinal and transverse
- up to 3 stand-alone spectrometers to cover several Q^2 points:
  Quadrupoles, dipoles, Cherenkov tanks, hodoscopes, EM calorimeters
- Data in late 70's and 90's

Some results….

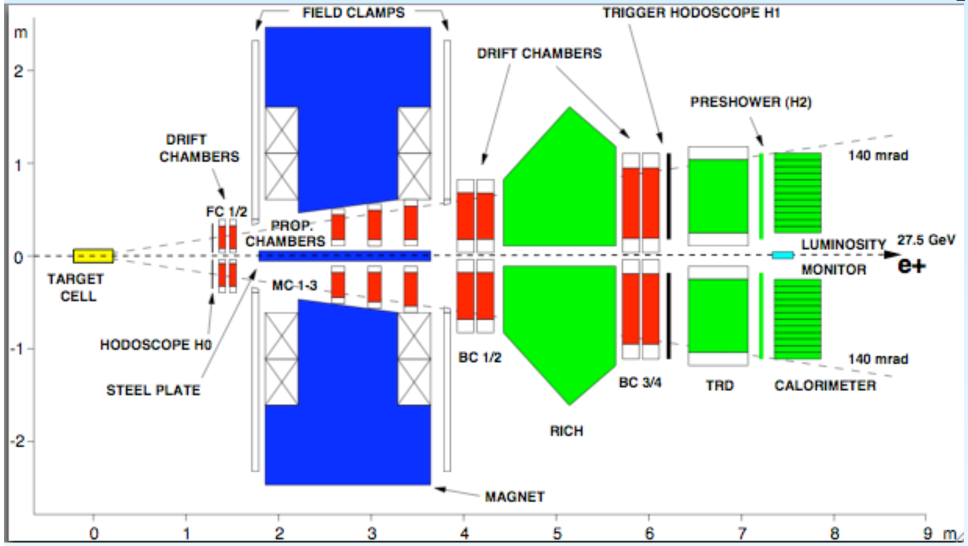
available data we find $\Gamma_1^p - \Gamma_1^n = 0.176 \pm 0.003 \pm 0.007$ at $Q^2 = 5$ GeV^2, in agreement with the Bjorken sum rule prediction of 0.182 ± 0.005.

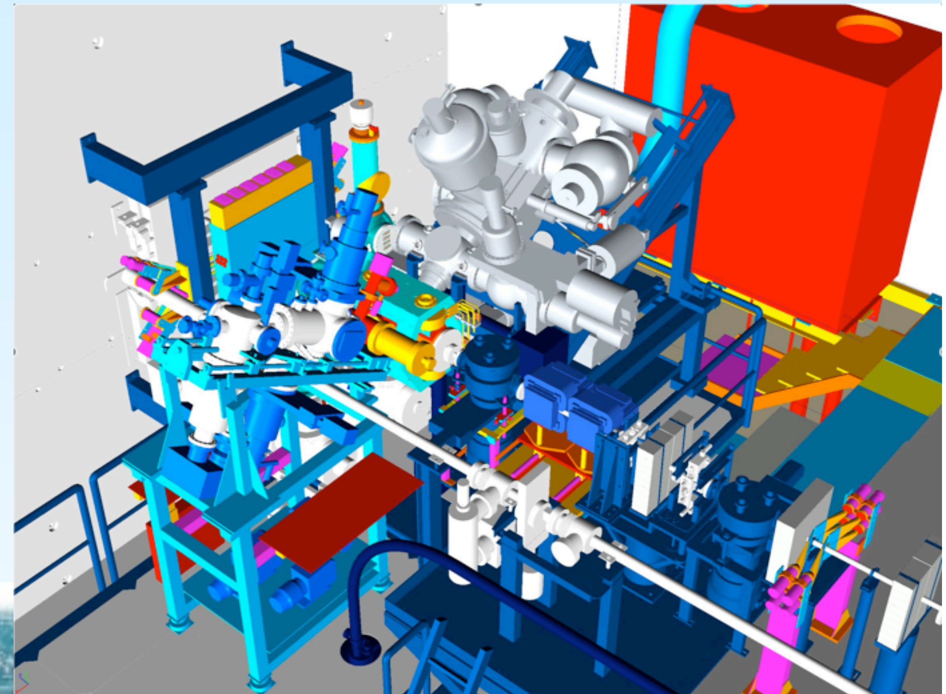






The HERMES Experiment at DESY

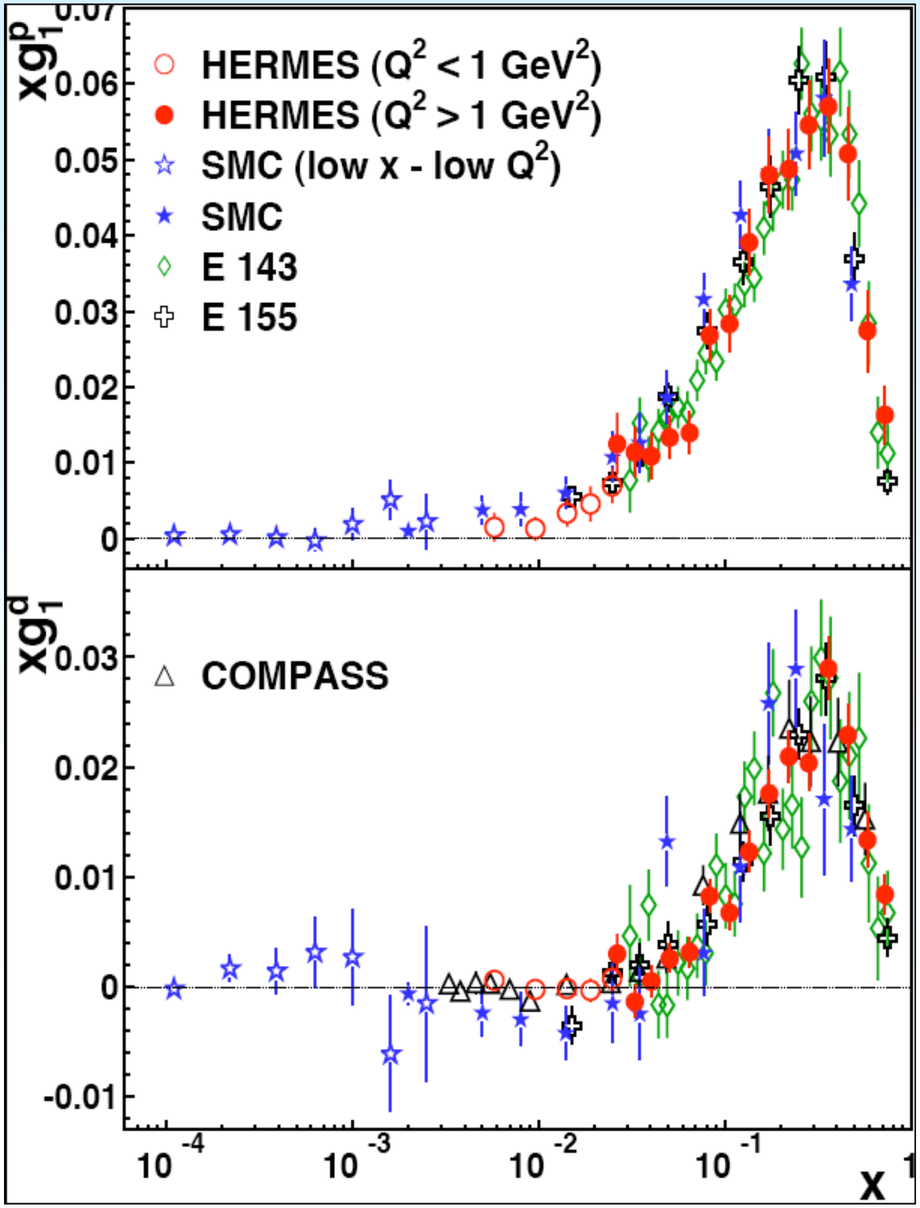


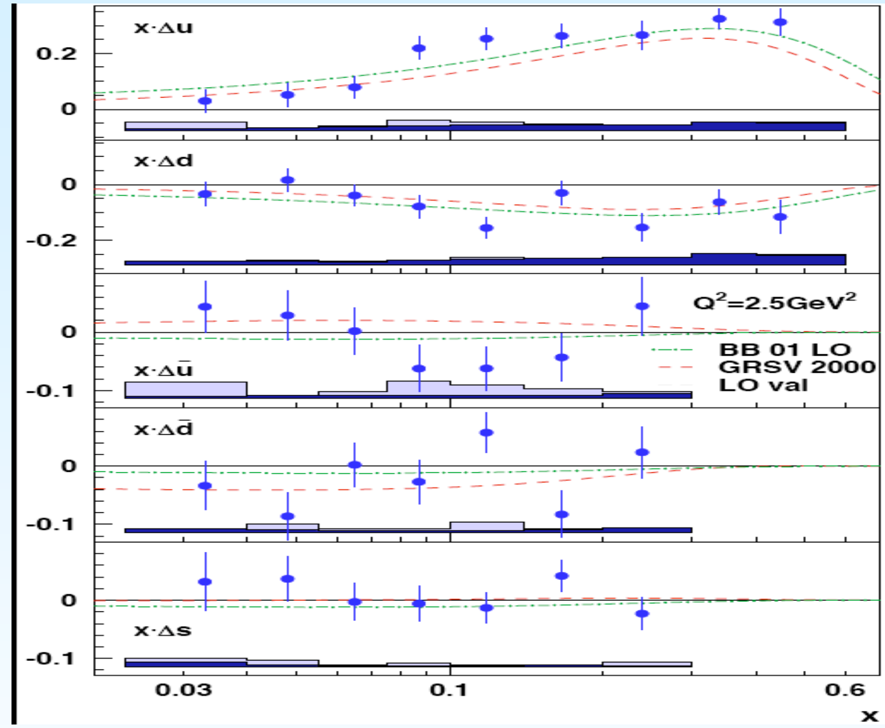


- Pure H,D, and ^{3}He gas jet targets, longitudinal and transverse
- 27 GeV e^{+} and e^{-} beams ("self-polarized")
- Inclusive, semi-inclusive and single-spin data 1995 - 2007

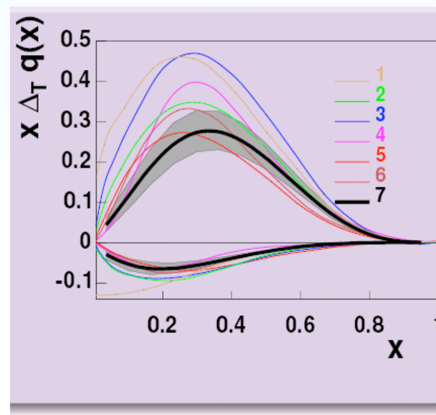
inclusive results…

… and semi-inclusive results





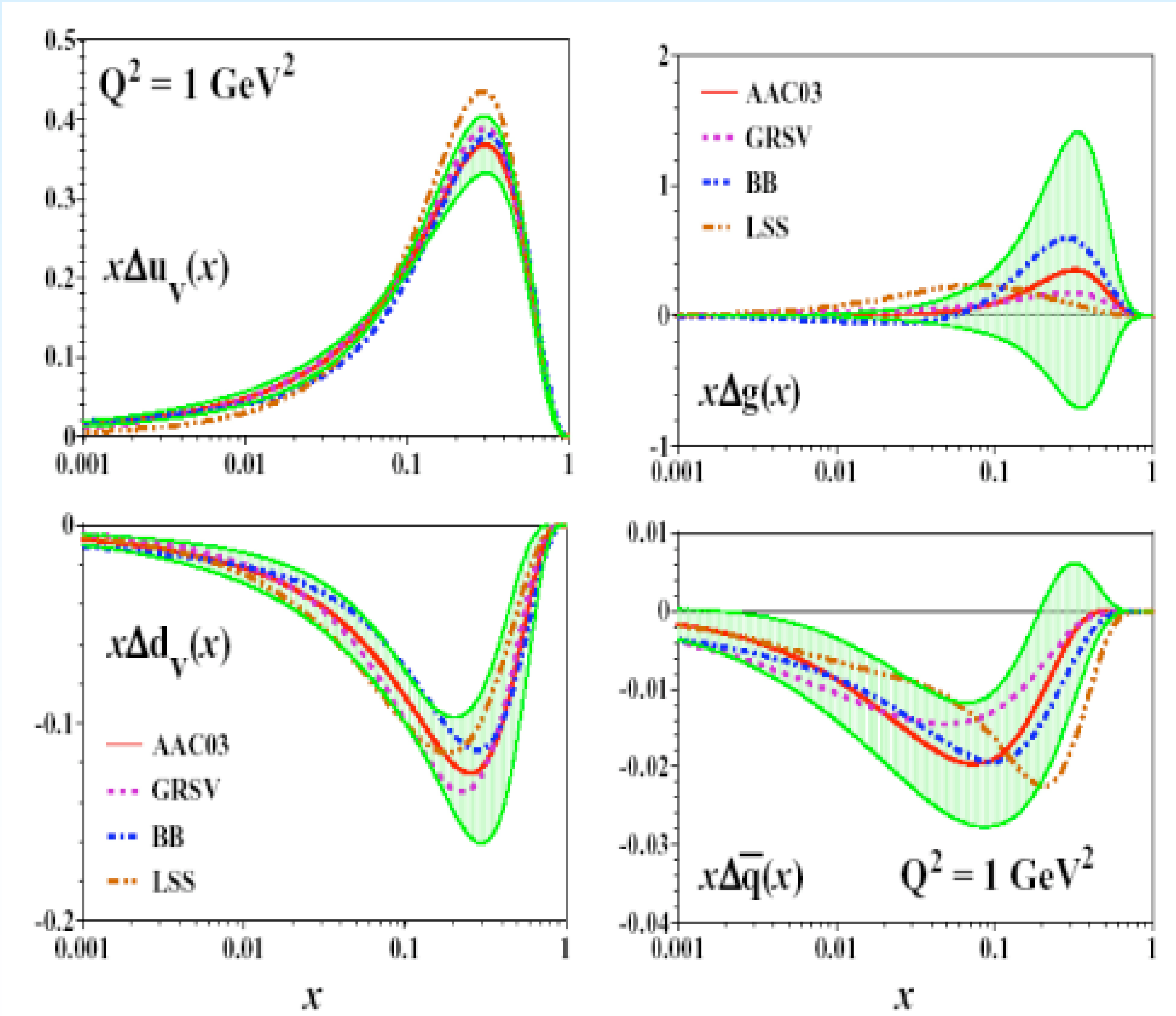
HERMES +COMPASS + Belle



1. Soffer et al. PRD 65 (02)
2. Korotkov et al. EPJC 18 (01)
3. Schweitzer et al. PRD 64 (01)
4. Wakamatsu, PLB B653 (07)
5. Pasquini et al., PRD 72 (05)
6. Cloet, Bentz and Thomas PLB 6 (08)
7. This analysis.

→ Status of polarized parton densities, ca 2003

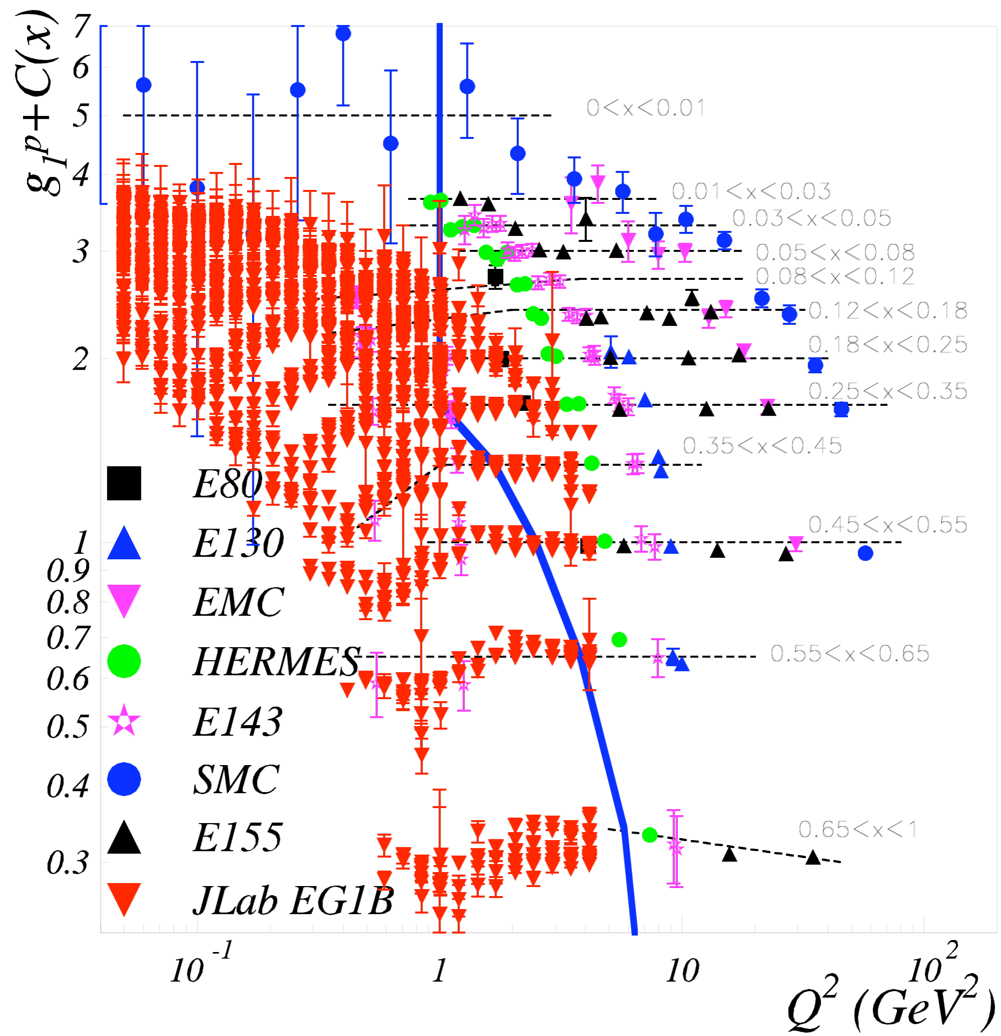
NLO analyses of all DIS data



Contributions from Jefferson Lab

World data on the proton before JLab
(without COMPASS)

World data on the proton including EG1
(without COMPASS)



JLab Experiments - Kinematic Coverage

"Everything"

Sum Rules at low Q^2

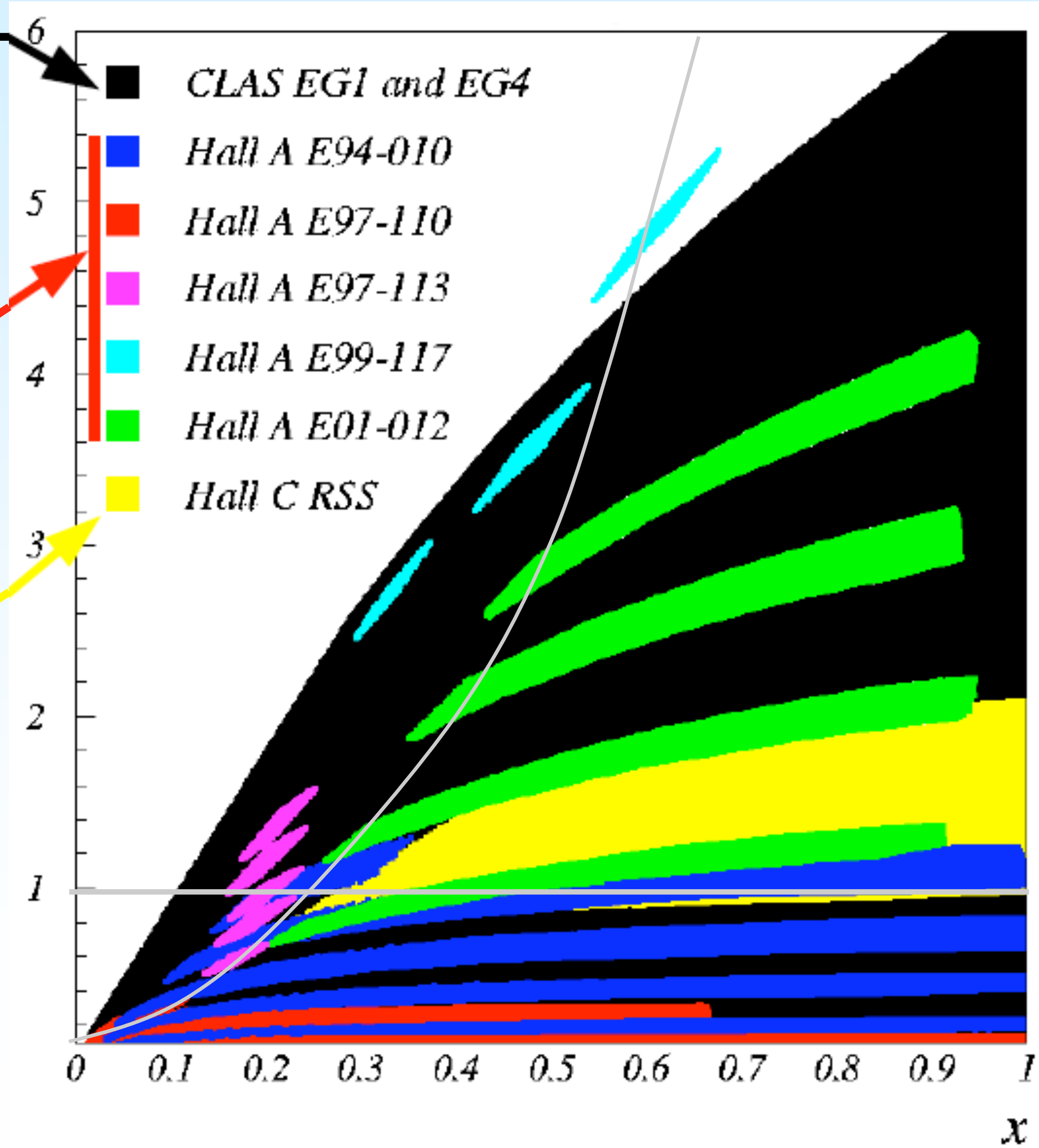
very low Q^2 - χPT

Q^2-dep. of g_2

A_{1n} at high x

Duality

Res. Region, Duality

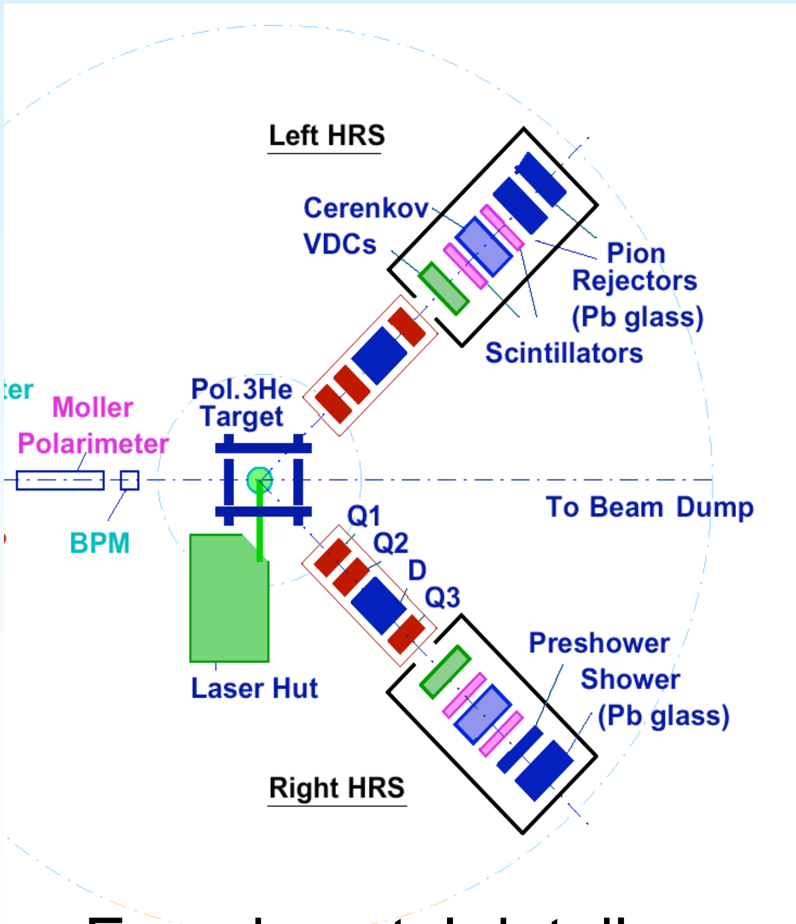


✓8 completed experiments

3 (+3) approved with 6 GeV JLab

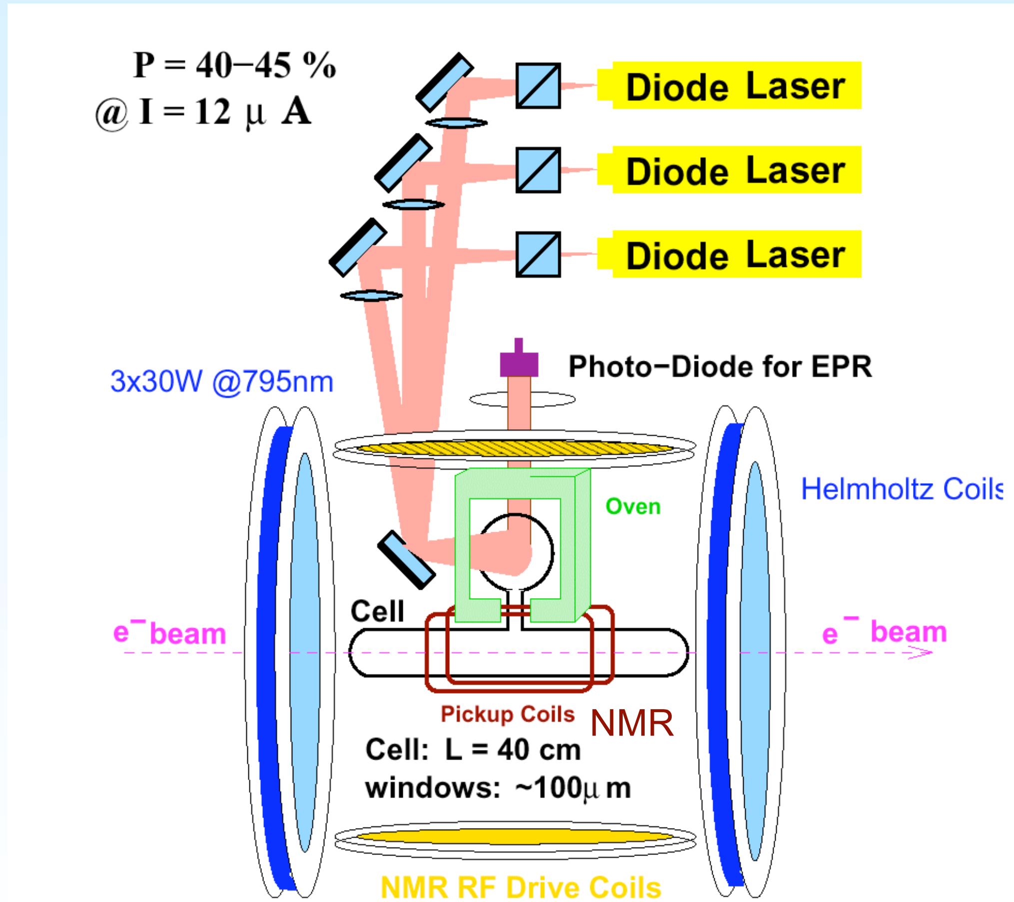
3 (+1) approved with 12 GeV (A/B/C)

Experiments in Jefferson Lab's Hall A



Experimental details

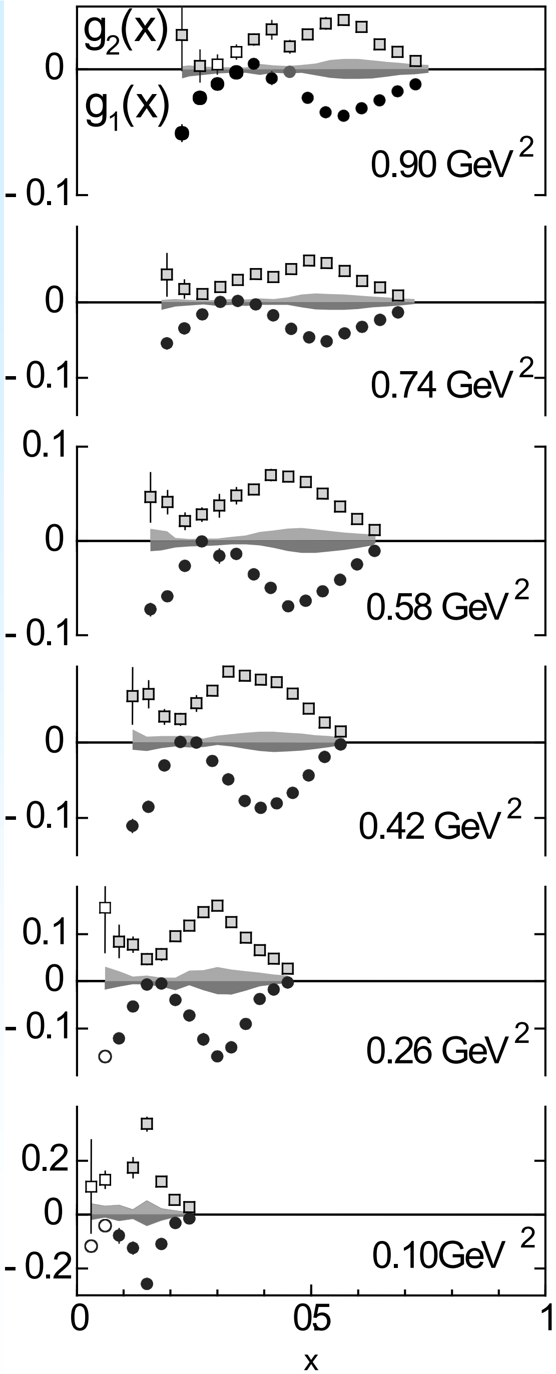
Luminosity: 10^{36} s^{-1} cm^{-2}



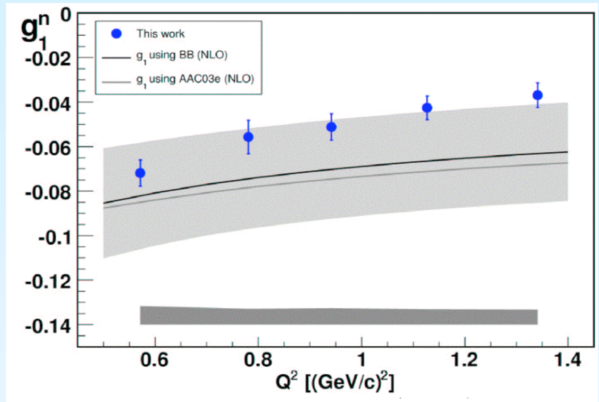
Polarized ^{3}He target: Spin exchange with laser-polarized alkalides; > 50% pol. (longitudinal and transverse)

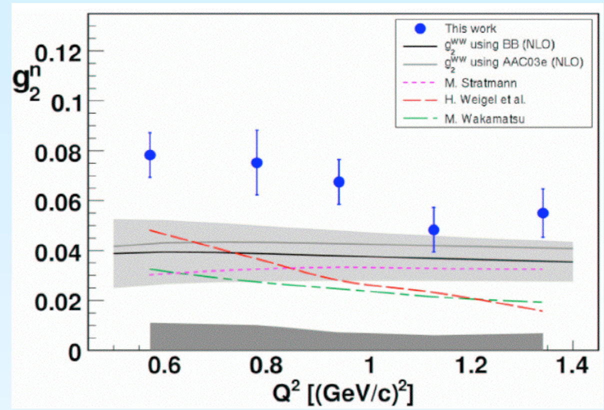
g_1 and g_2 for n (^{3}He)

Hall A



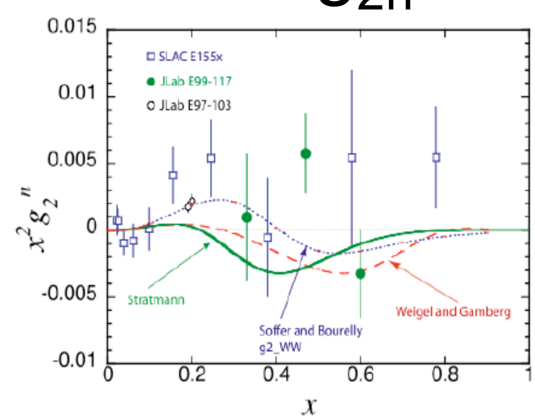
E94-010



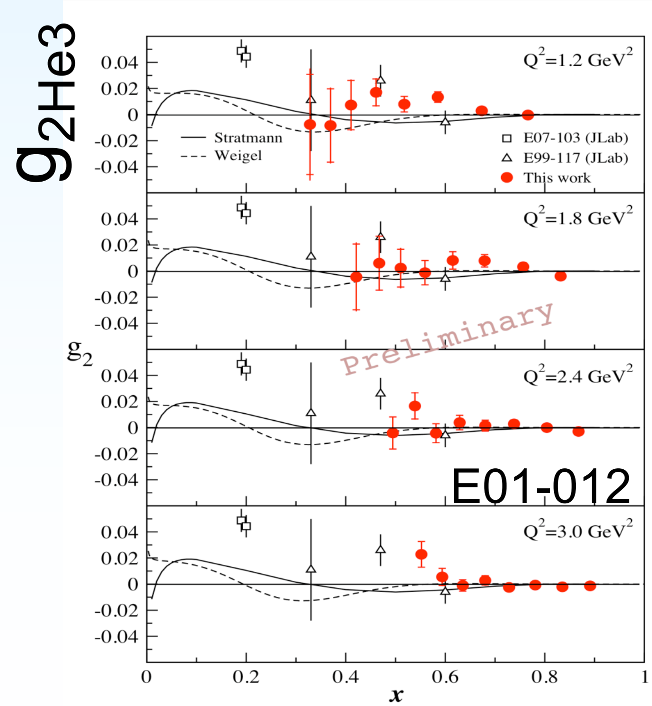


Q^2 evolution in one x-bin 0.16 - 0.2 (E97-103)

g_{2n}



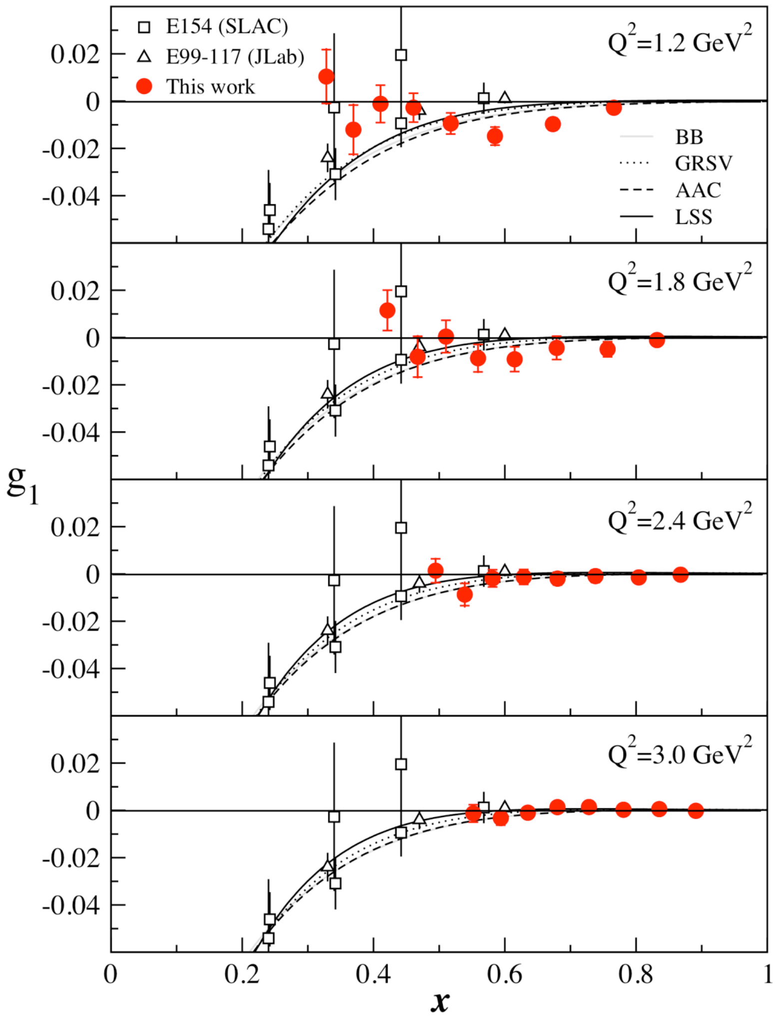
- SLAC E155x (proton and deuteron)
- JLab E99-117(helium-3), A_1^n in DIS
- Jlab E97-103 (helium 3) DIS, Q^2 dependence mainly below 1.4 GeV^2

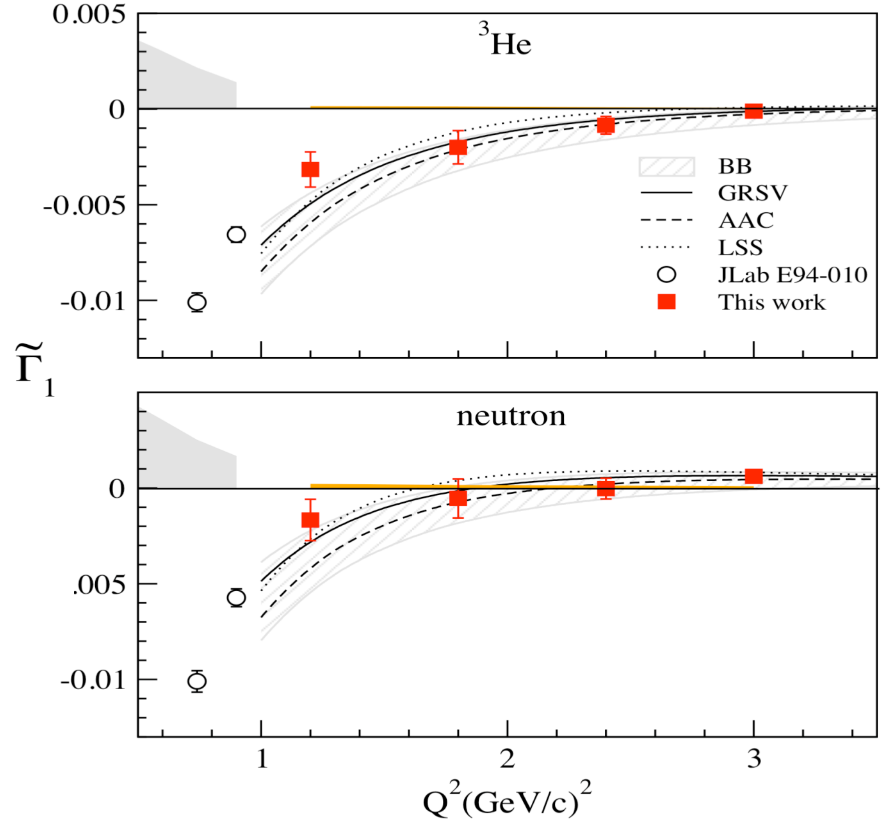


Spin duality on ^{3}He

Hall A

P. Solvignon et al., arXiv:0803.3845 (submitted to PRL)



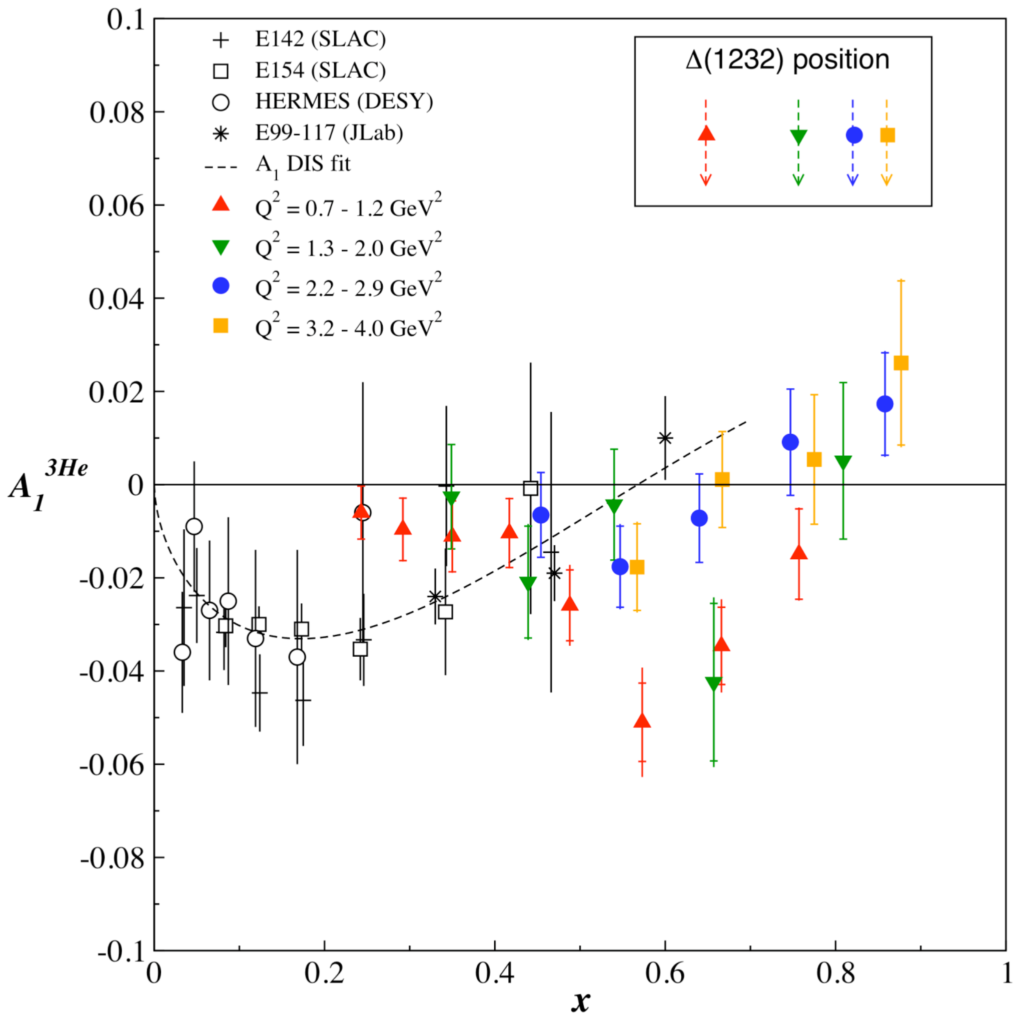


Target mass corrections were applied on PDFs

A_1 for ^3He

Hall A

P. Solvignon et al., arXiv:0803.3845 (submitted to PRL)



Large negative value in the Δ (1232) region

Still large negative value in the Δ(1232) region

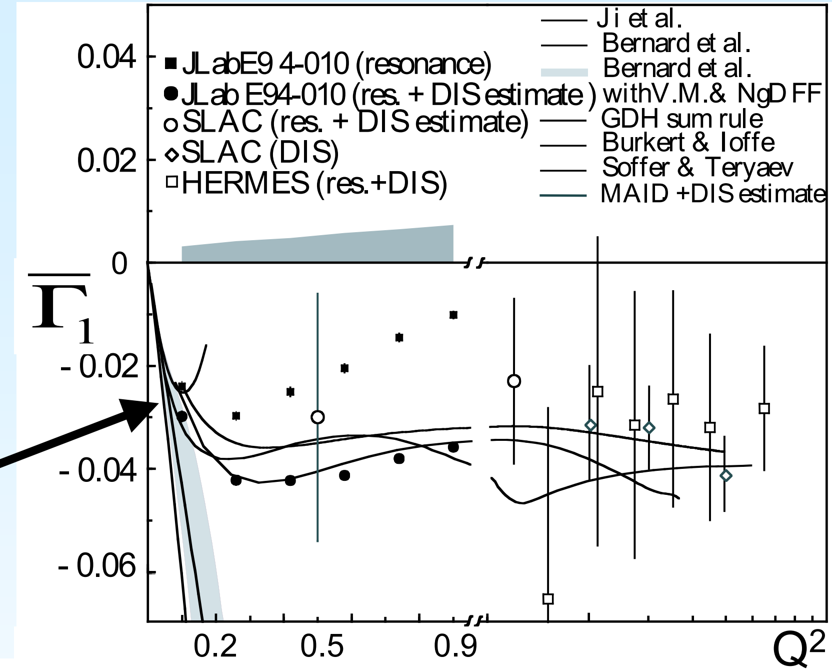
A_1 becomes positive in the Δ (1232) region due to the drop in the Δ FF and the rising of the DIS background

No strong Q^2-dependence is now observed

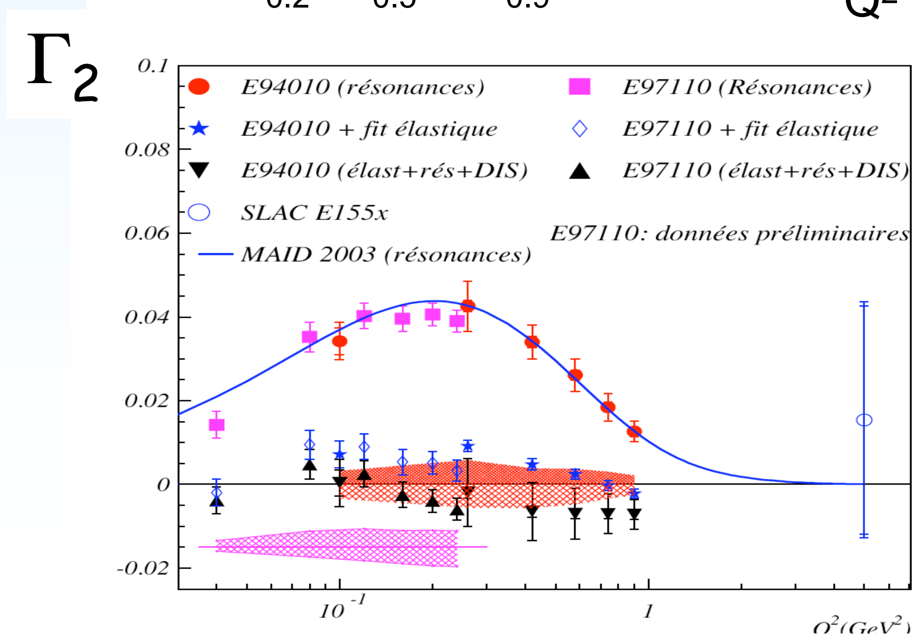
First Moments for the neutron

Hall A

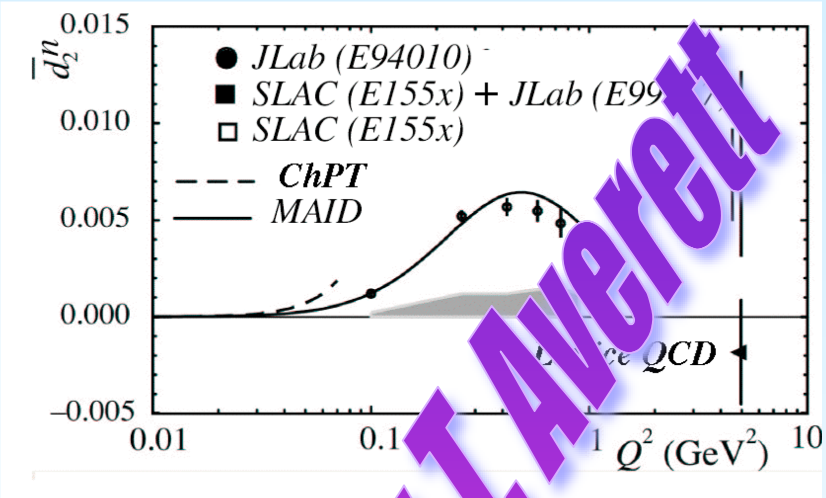
Lowest point, Q^2 = 0.1, is consistent with χPT calculations (Ji, Bernarnd) and with the slope of the GDH sum rule.



Seems to be compatible with Burkhardt-Cottingham sum, within uncertainties.



Twist-3 Matrix element d_2



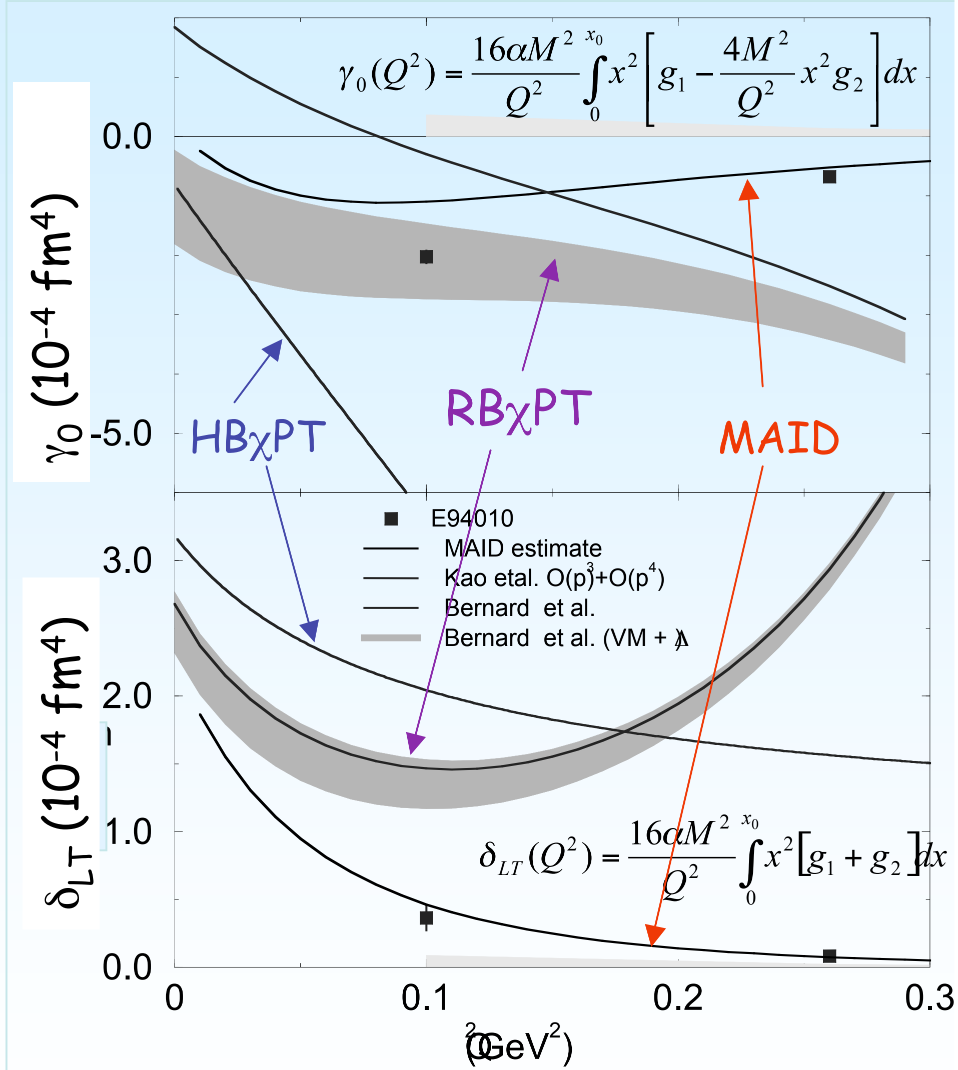
+

GDH integral on the neutron

+

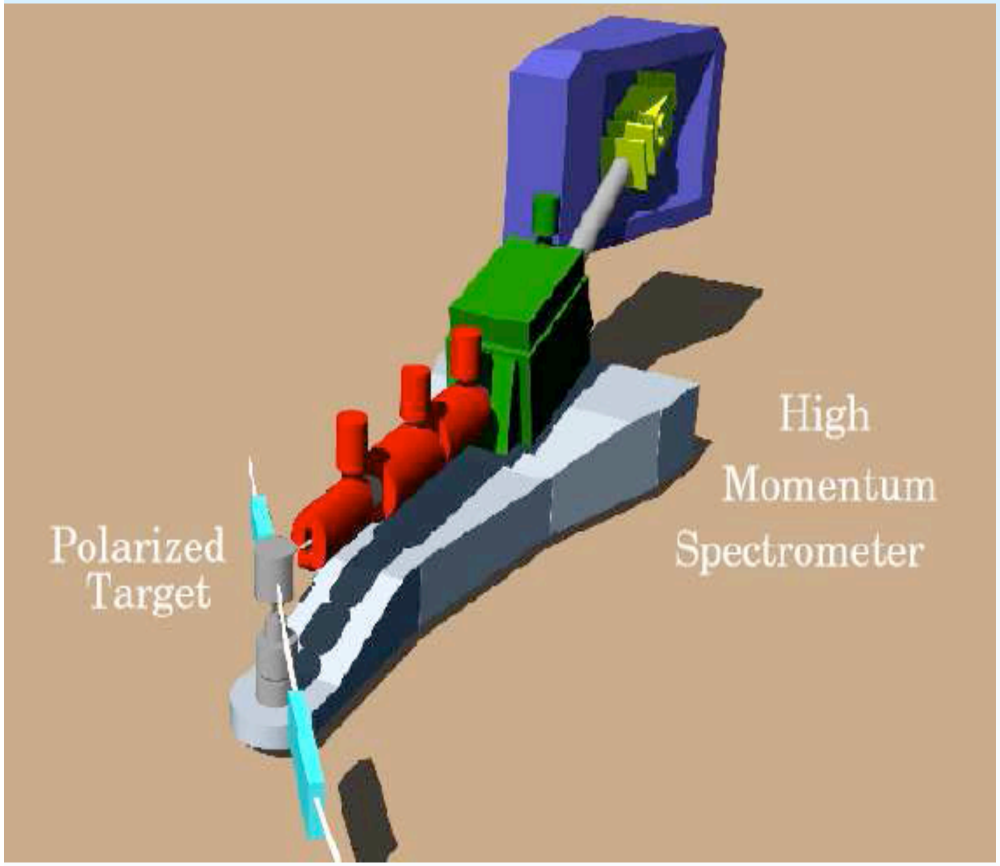
…

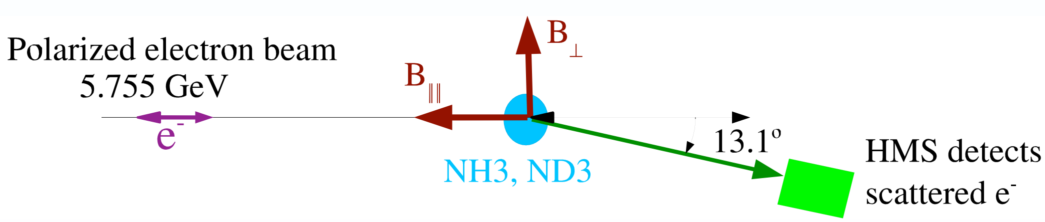
Neutron Polarizabilities

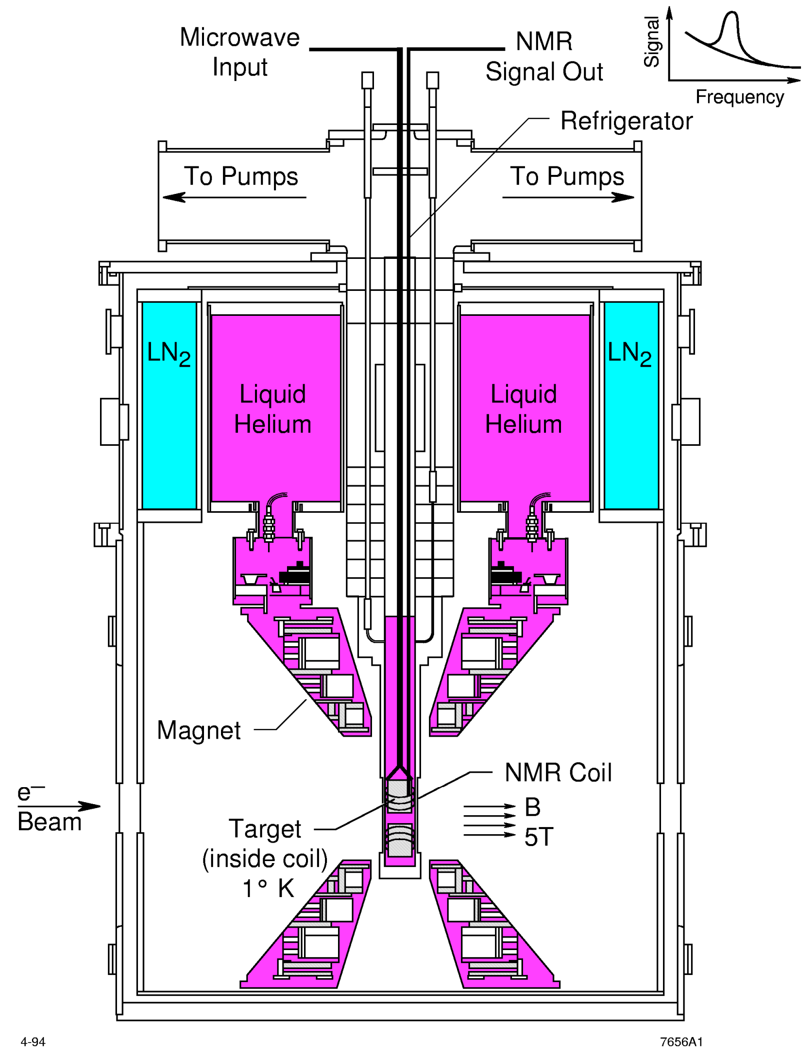


RBχPT + Δ and vector mesons

The RSS Experiment in Hall C



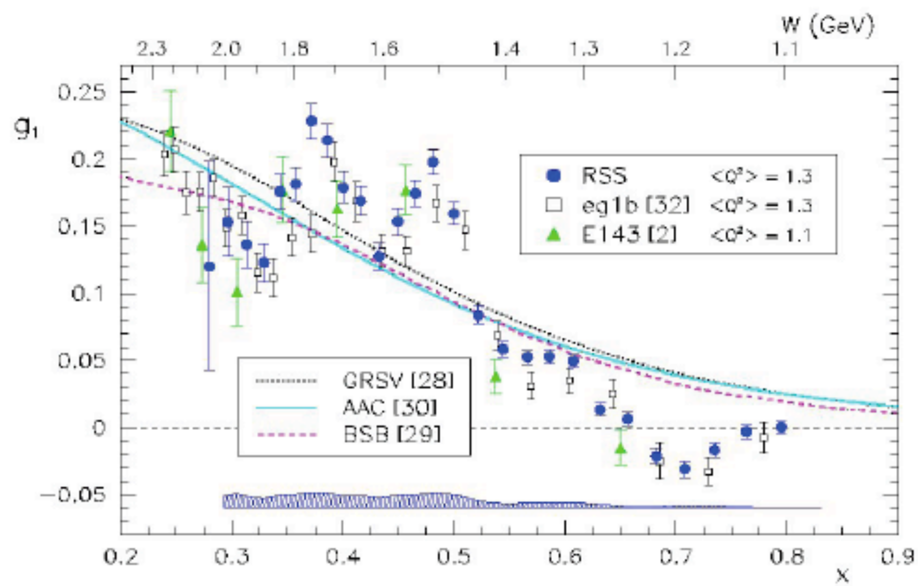


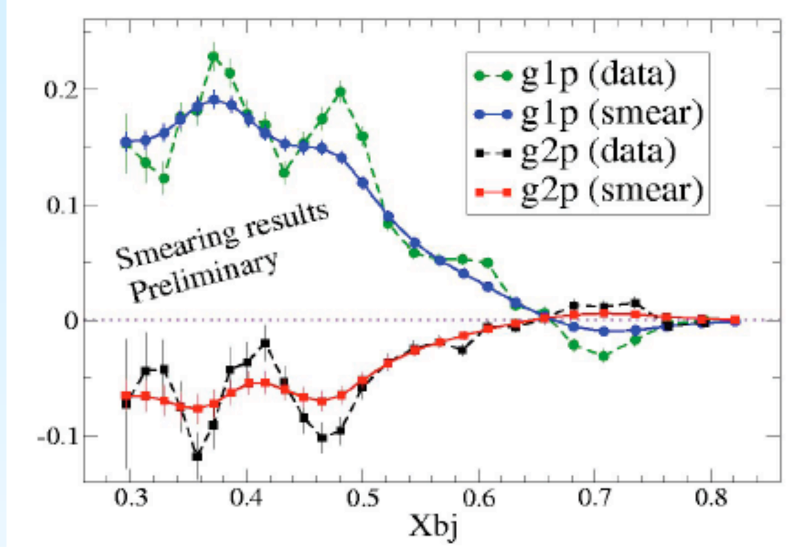


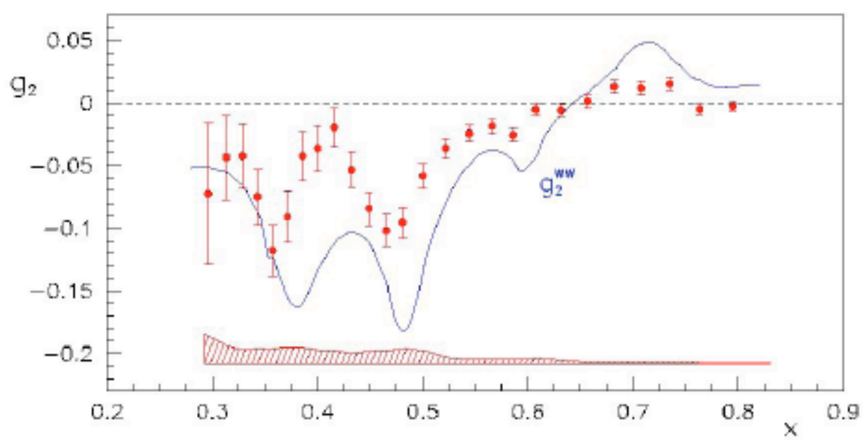
Polarized p/d target

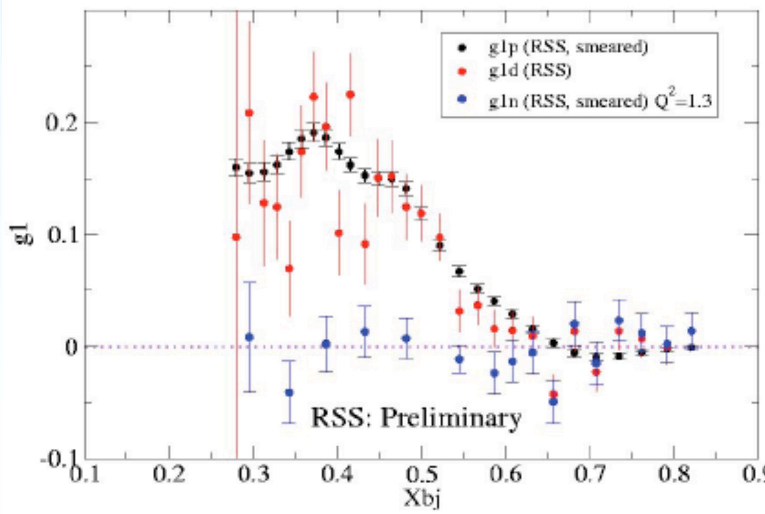
g_1 and g_2 on p and d

Hall C







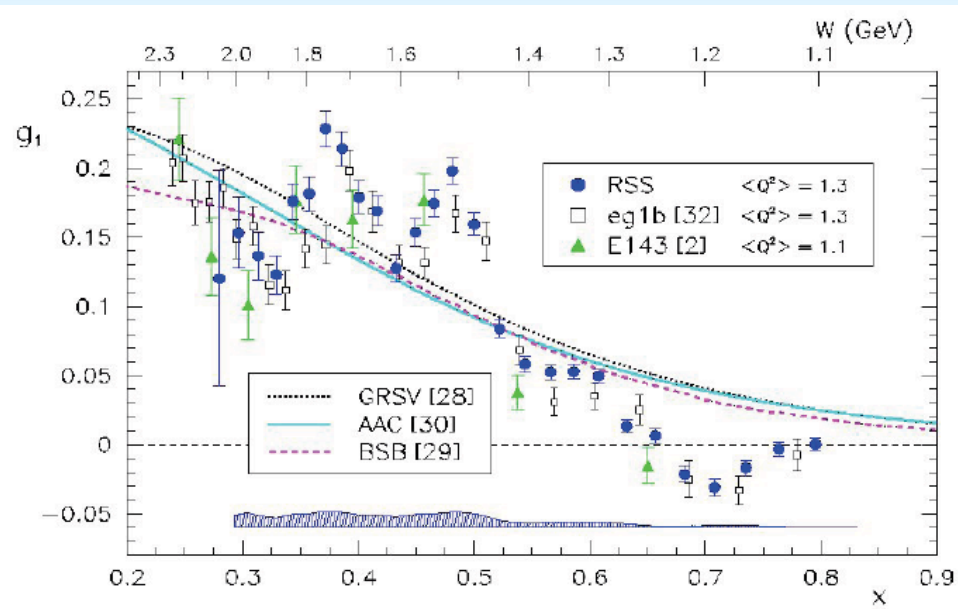


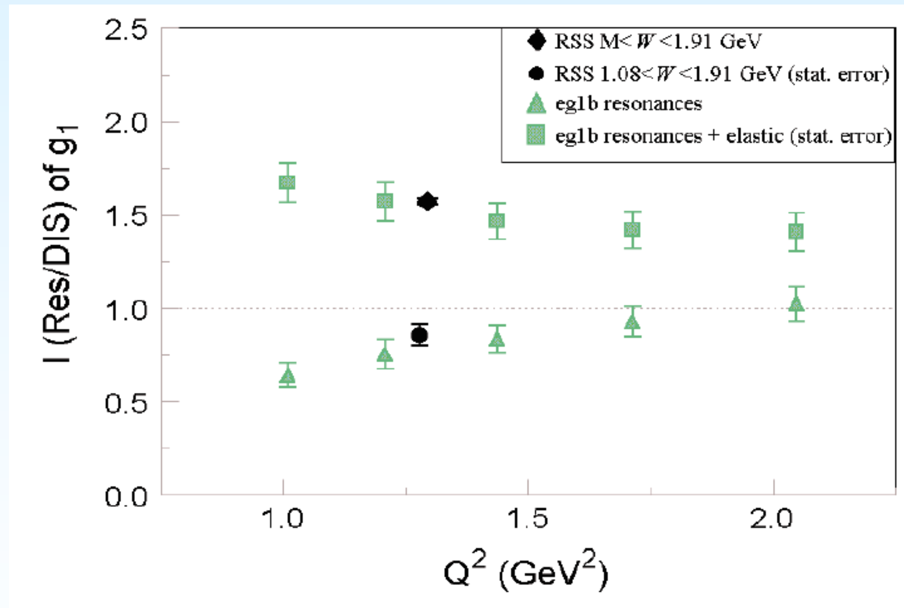
Q^2 = 1.3 GeV^2

Duality

Hall C

Comparing g1p in resonance region with extrapolated DIS results





Even at Q^2 = 1.3 GeV^2 strong fluctuations of $g_{1p}(x,Q^2)$ around DIS

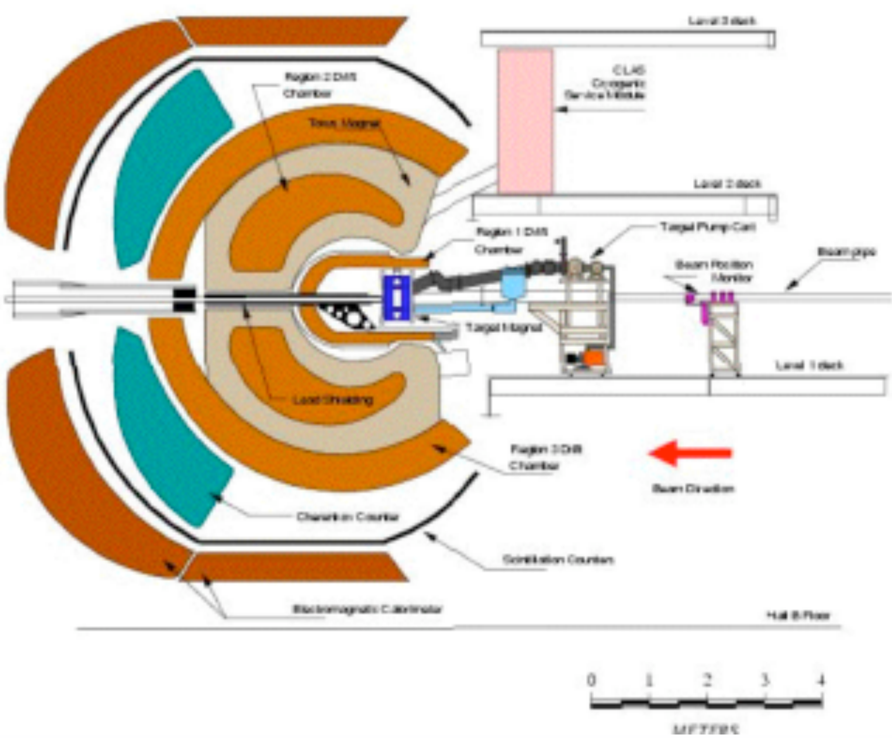
Global duality becomes fairly reasonable above Q^2 = 1.5 GeV^2

Experiments EG1 and EG4 with CLAS

EG1: $Q^2 = 0.05 \ldots 5\ \mathrm{GeV}^2$

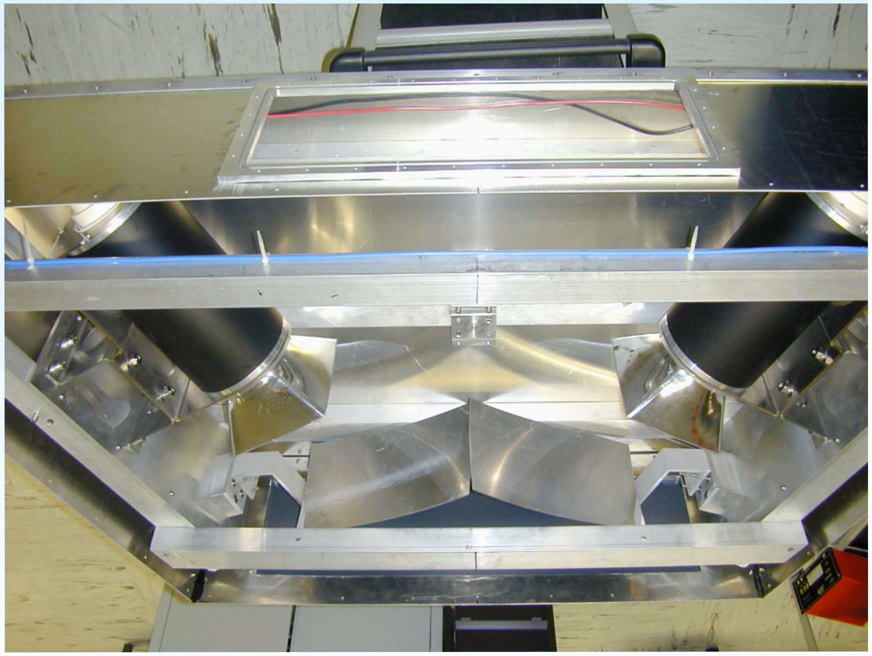
Largest possible kinematic coverage
→ inbending and outbending
configuration, E = 1.6…5.8 GeV

1998 - 2001



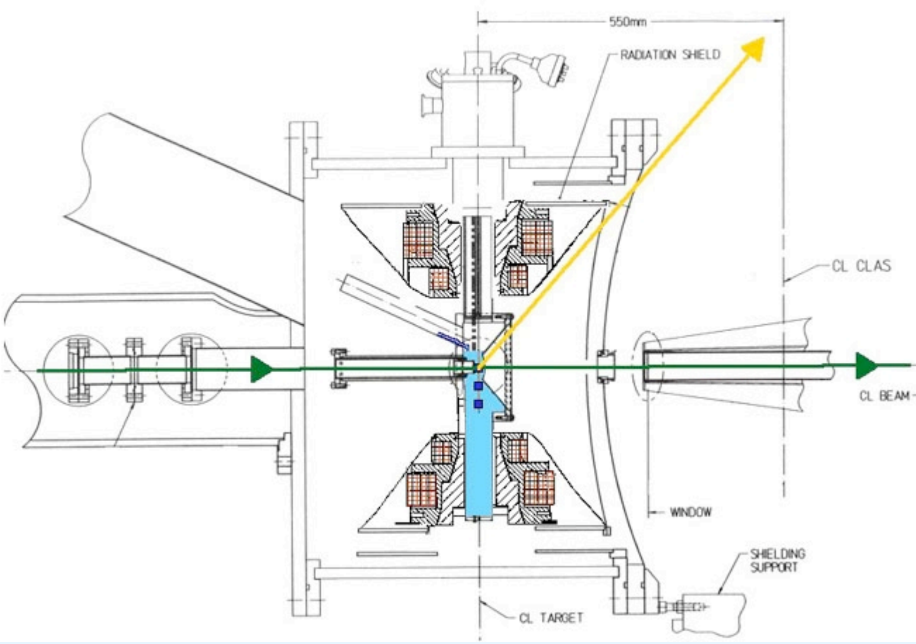
EG4: $Q^2_{min} = 0.015\ \mathrm{GeV}^2$

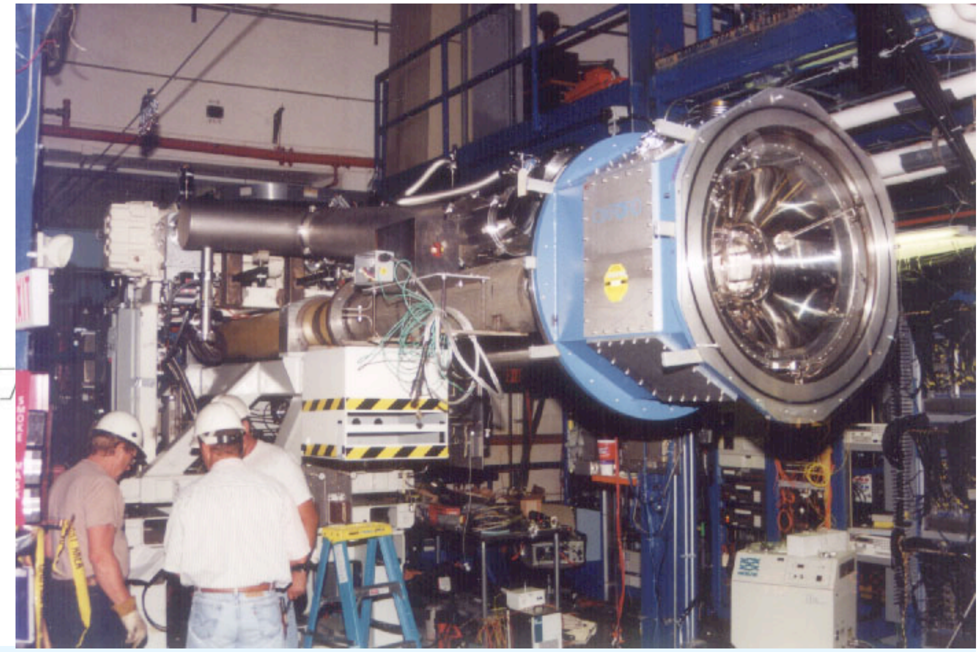
note: $m_\pi^2 = 0.02\ \mathrm{GeV}^2$



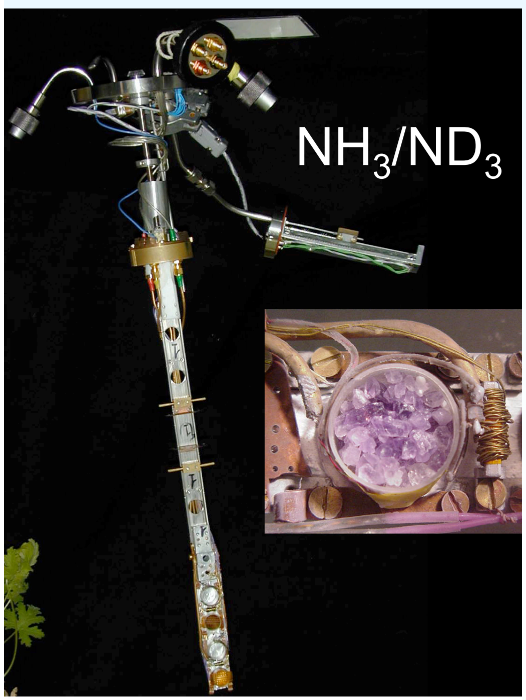
Focus on low Q^2 (GDH, χPT) => lower beam energies, new Cherenkov for optimal acceptance in outbending configuration, θ_e as small as 6 degrees

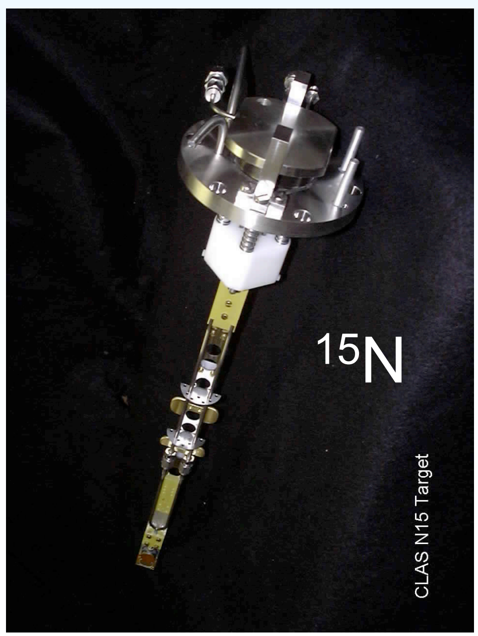
2006

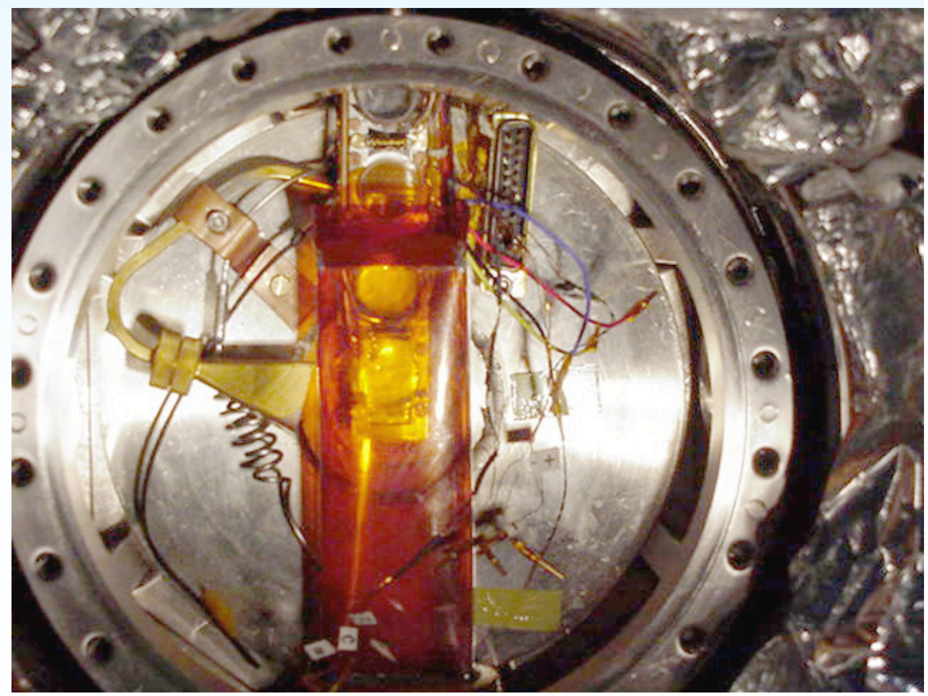




EG1/EG4 target (CLAS): Polarization up to 0.9 (p) or 0.4 (d)



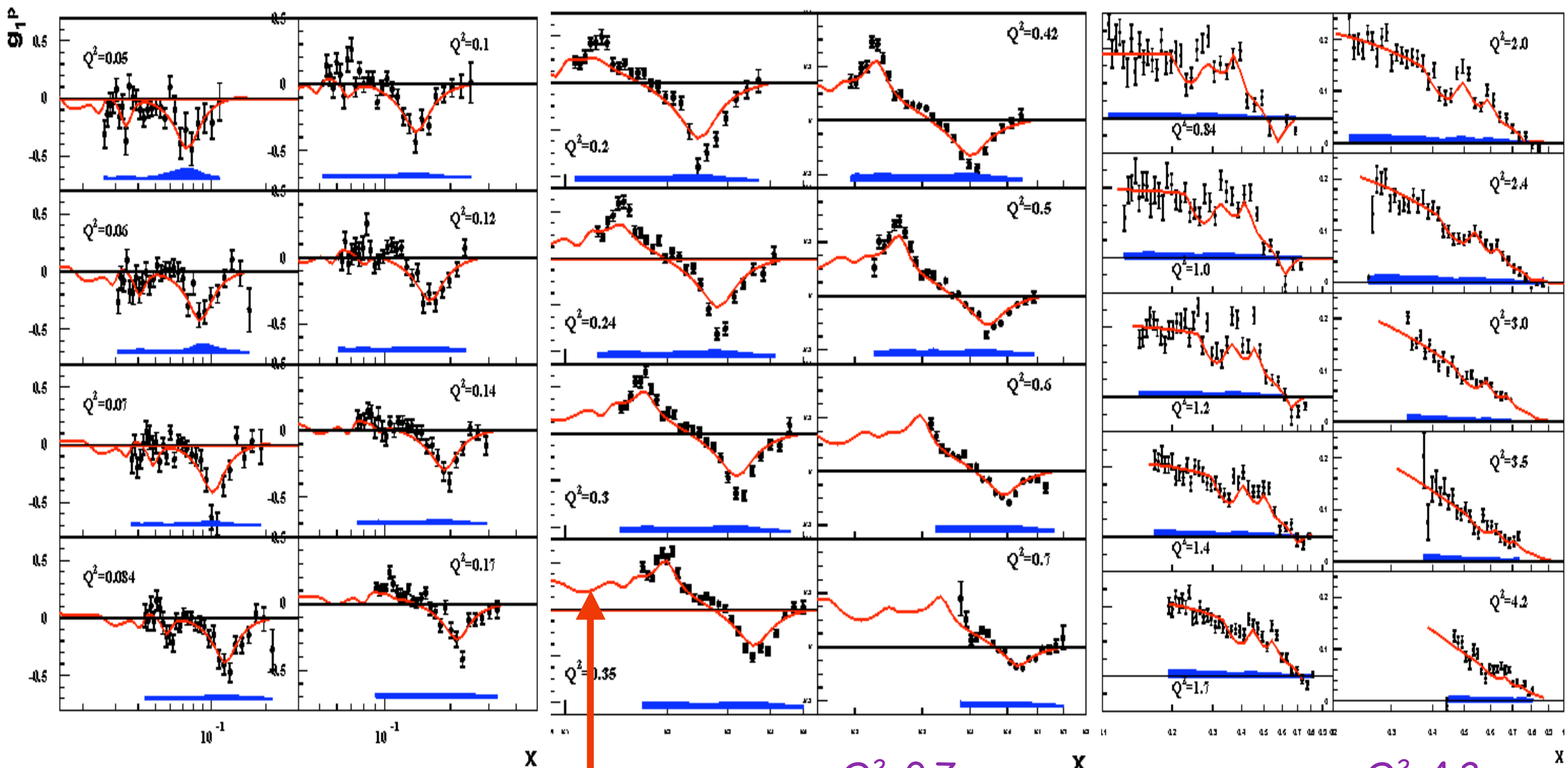




g_1^p from 1.6 GeV and 5.7 GeV EG1 data

Hall B

Q^2=0.05 Q^2=0.2 Q^2=0.84

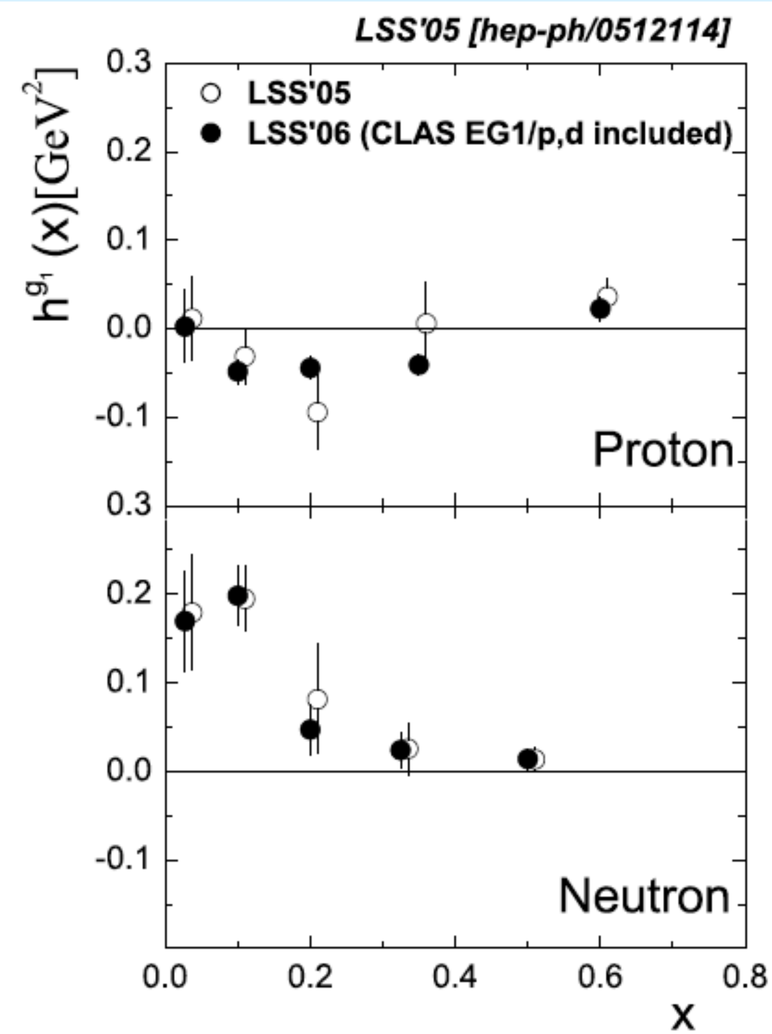


Q^2=0.7 Q^2=4.2

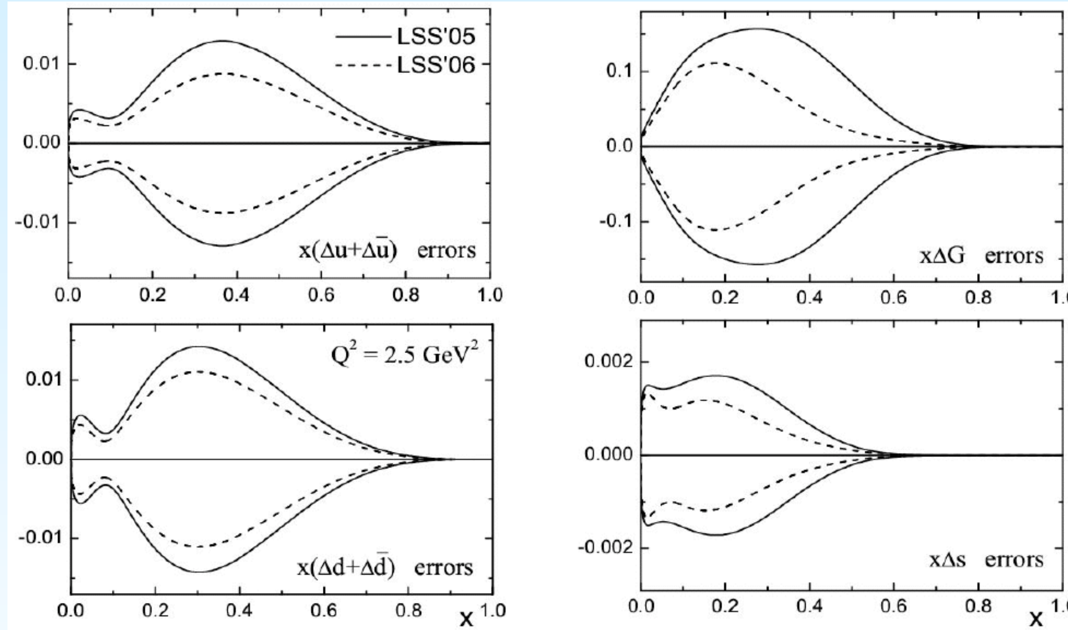
parametrization of world data

Similar for deuteron...

Effect of CLAS data on NLO fits of PDFs



Higher Twist contribution to g_1

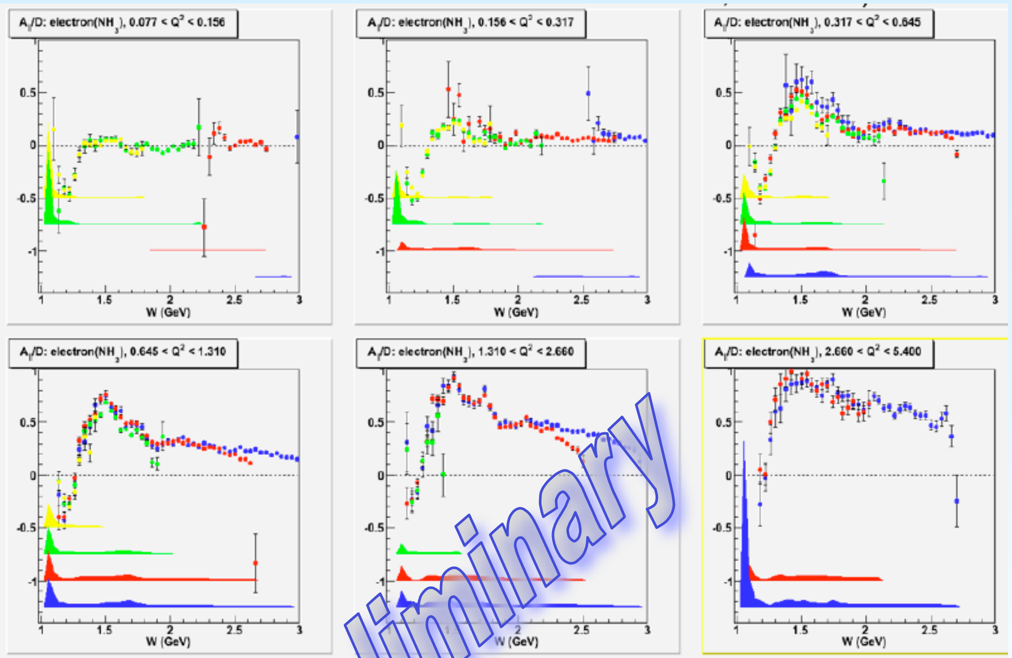


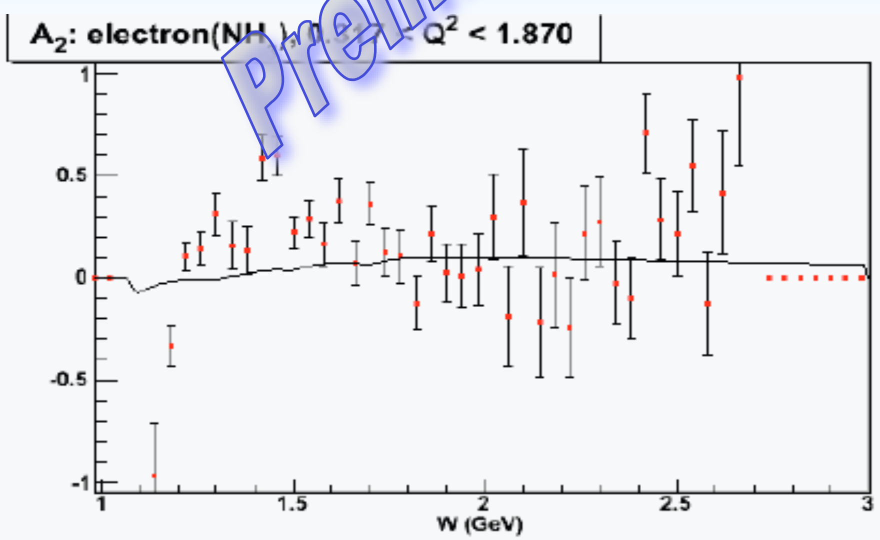
New NLO fit by Leader, Stamenov and Siderov, including both CLAS data and new COMPASS data on the deuteron

Presently under analysis

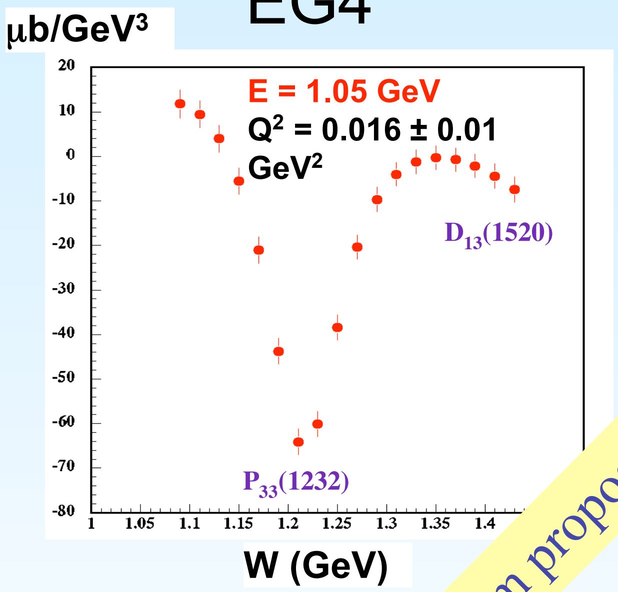
Hall B

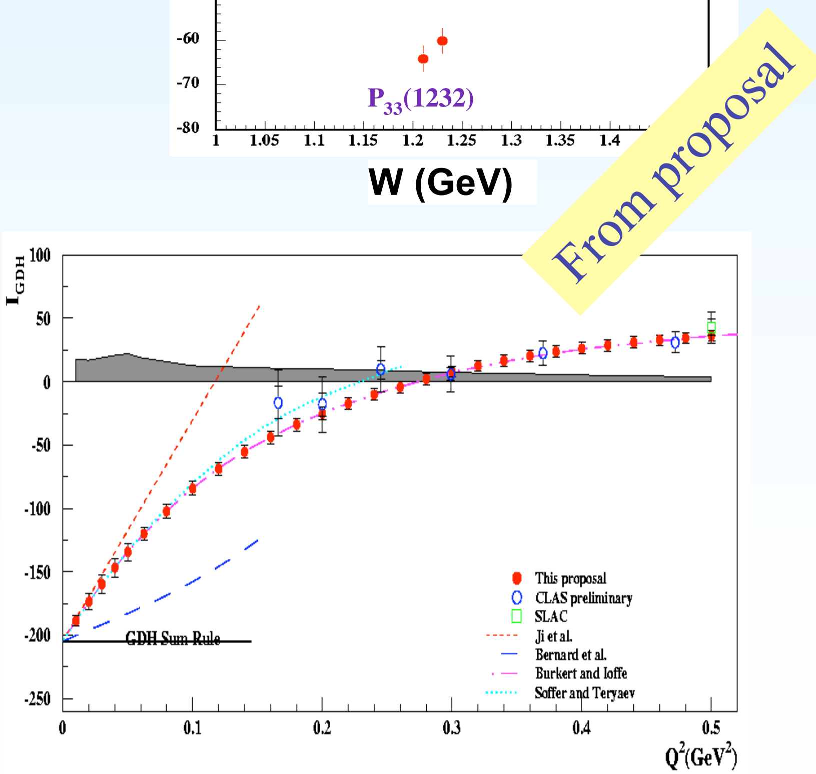
EG1





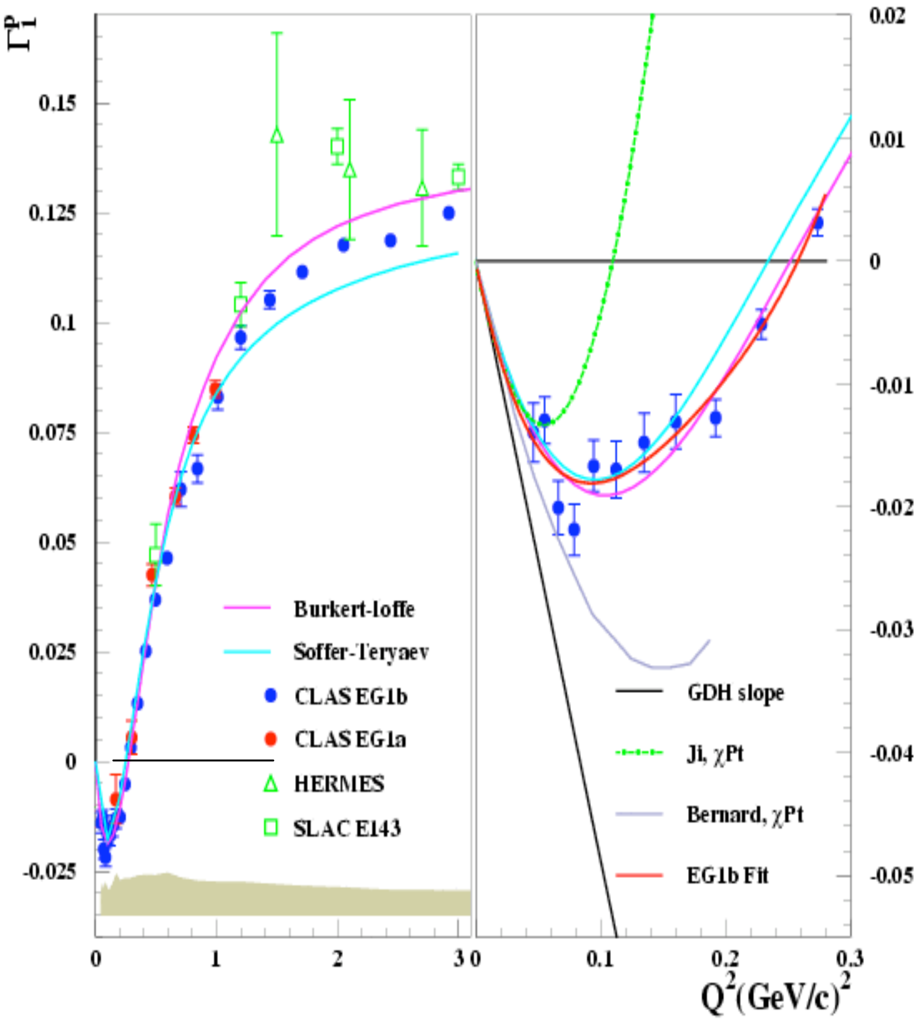
EG4



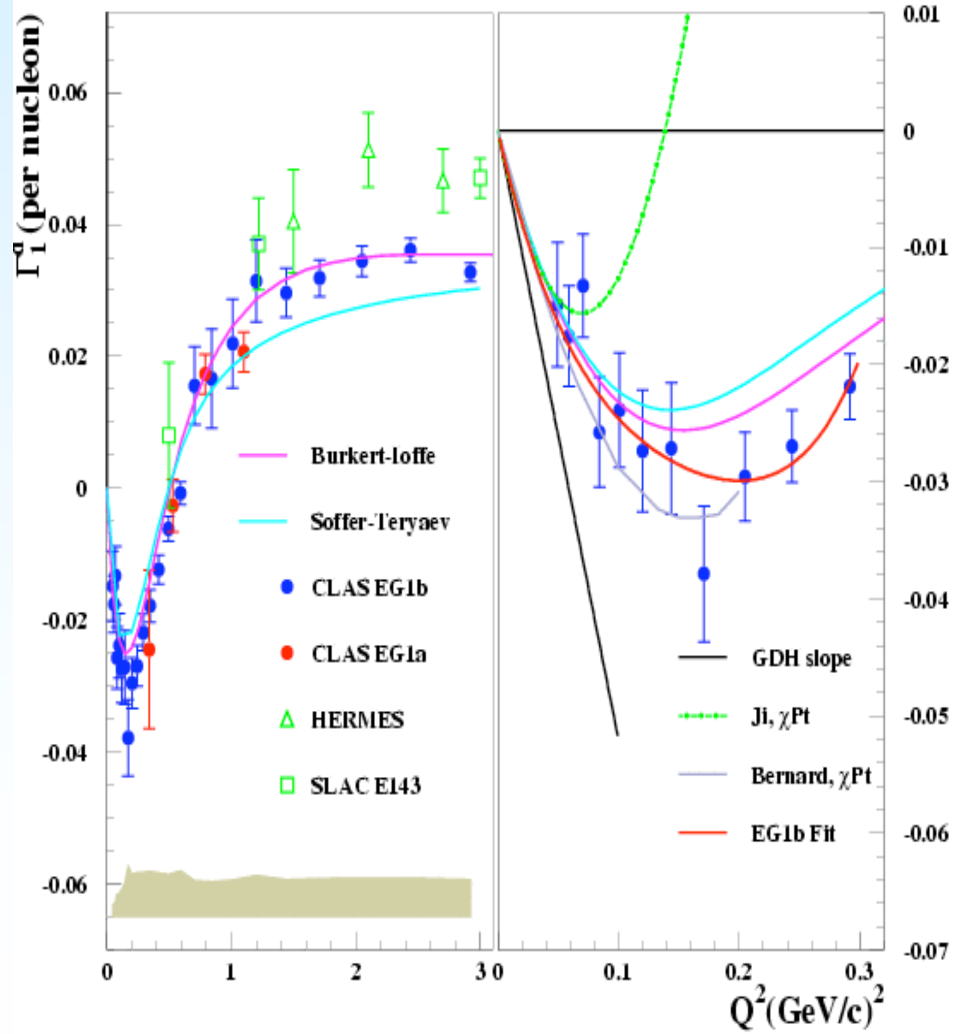


Moments and Sum Rules

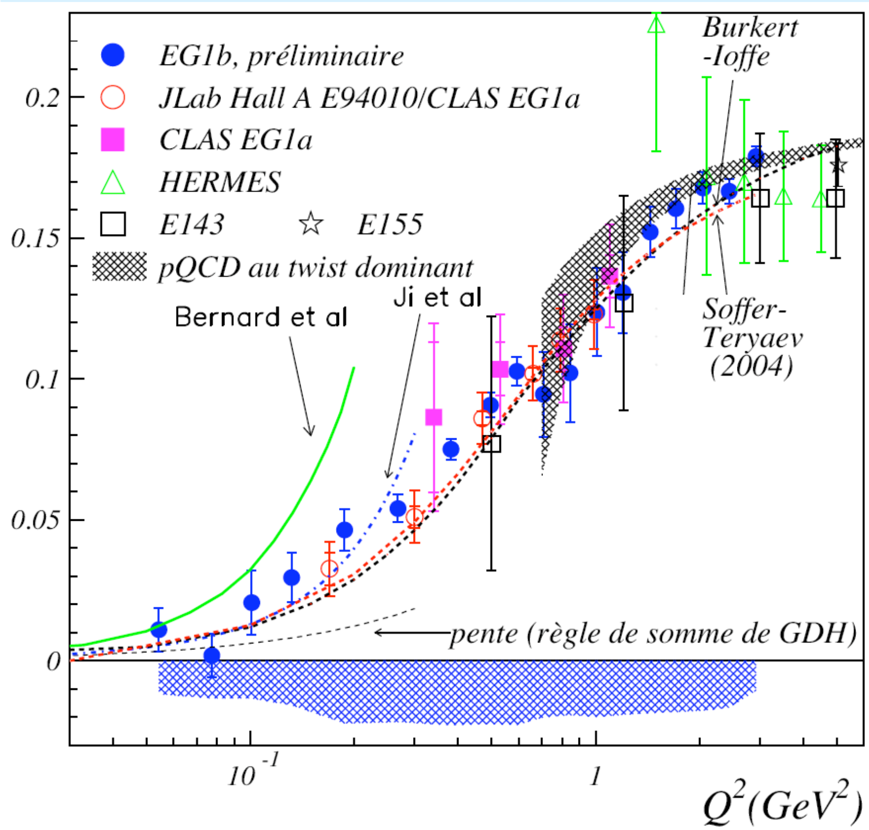
Γ_{1p}: First moment of g_{1p}



Γ_1 for the deuteron

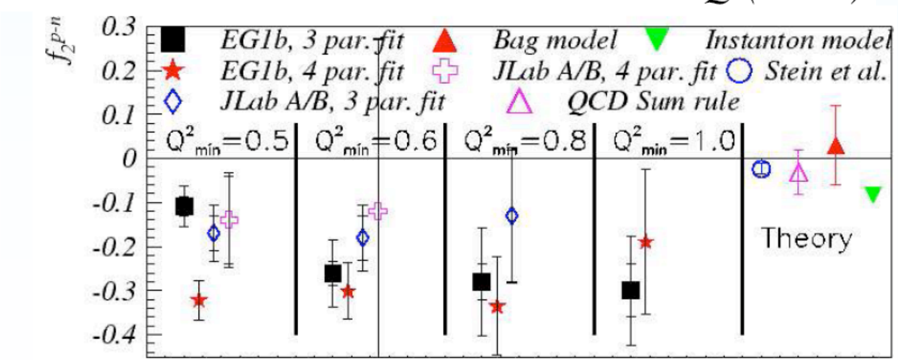


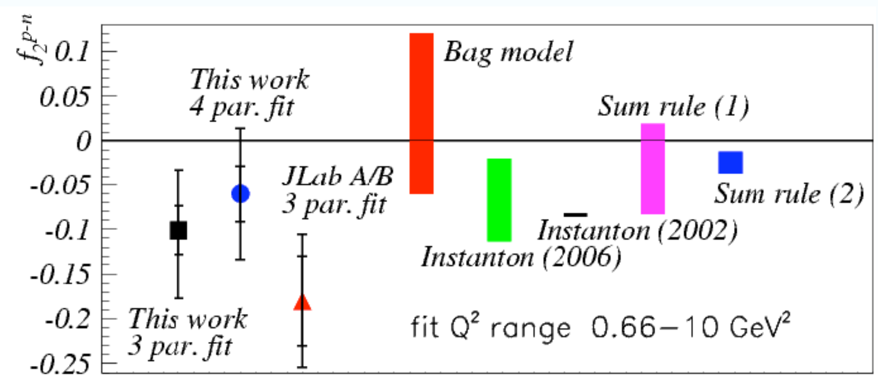
Combined Analysis: Bjorken Sum



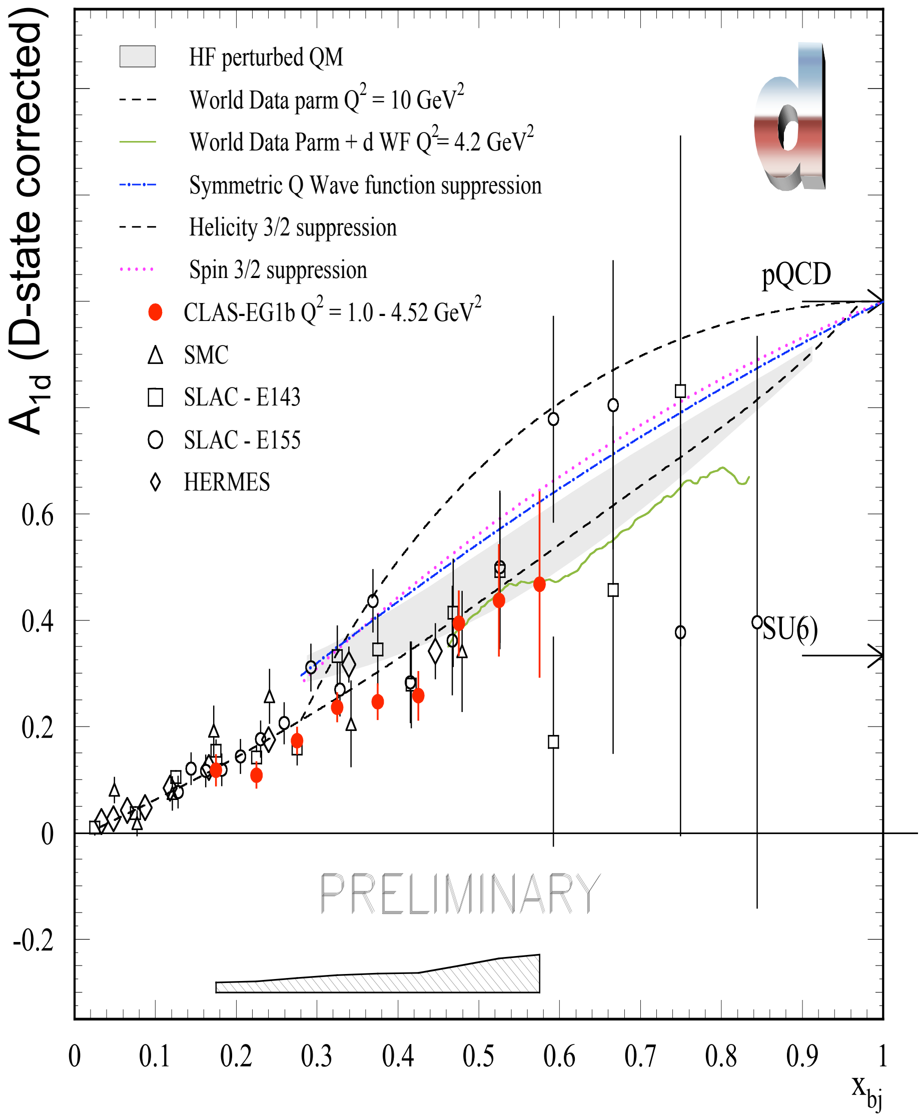
Bjorken-integral $\Gamma_1^{p\text{-}n}$

- Good agreement between all data sets
- Well described by 3-order pQCD at high Q^2
- Low Q^2 behavior smoother (Delta cancels)
- Can extract $f_2^{p\text{-}n}$ from Q^2-dependence

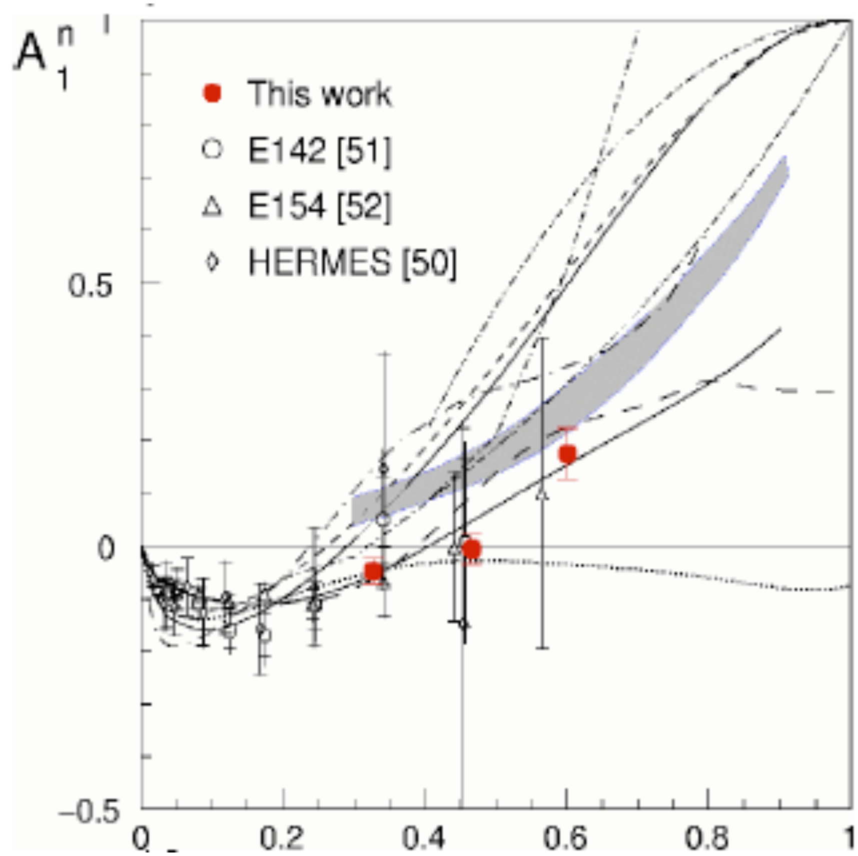




Virtual photon asymmetry A_1



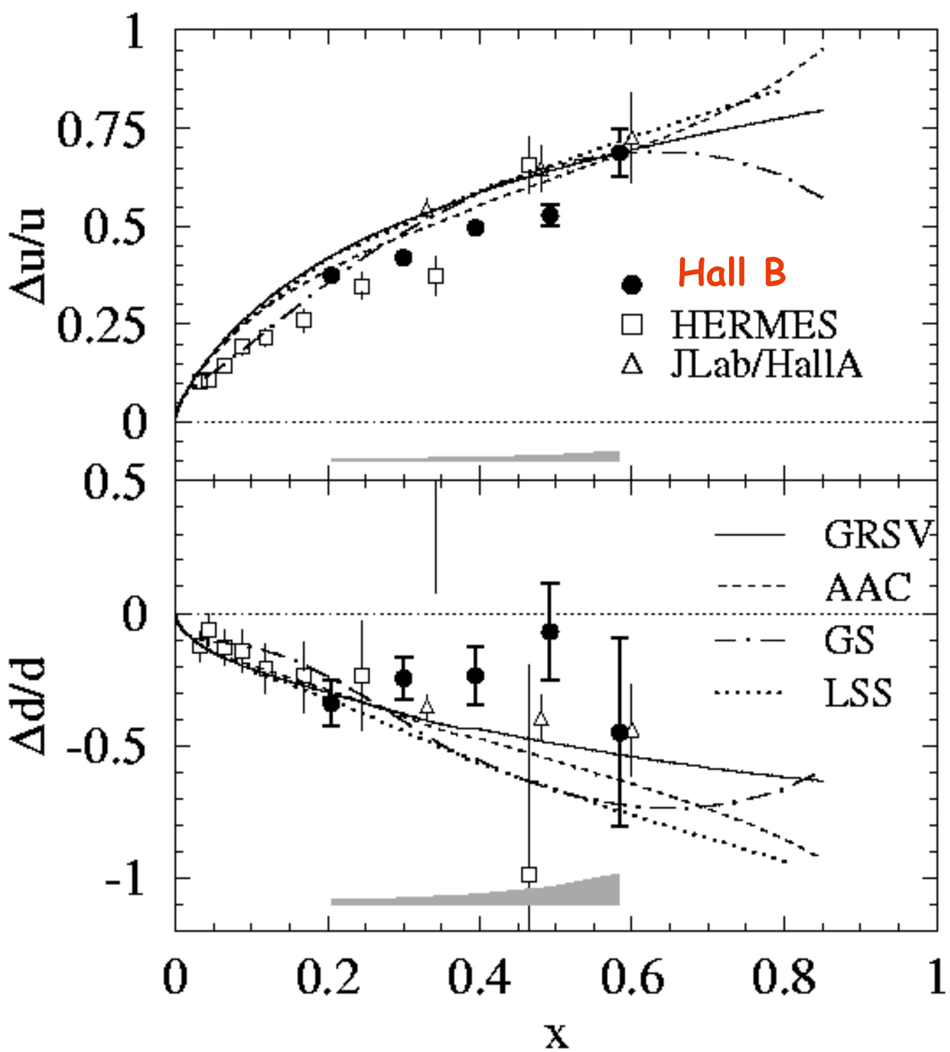
Hall A



N. Isgur, Phys. Rev. D 59, 34013

F. Close and W. Melnitchouk, Phys. Rev. C 68, 035210

Combined analysis: “naïve” quark polarizations



- Contribution from the s quark is ignored

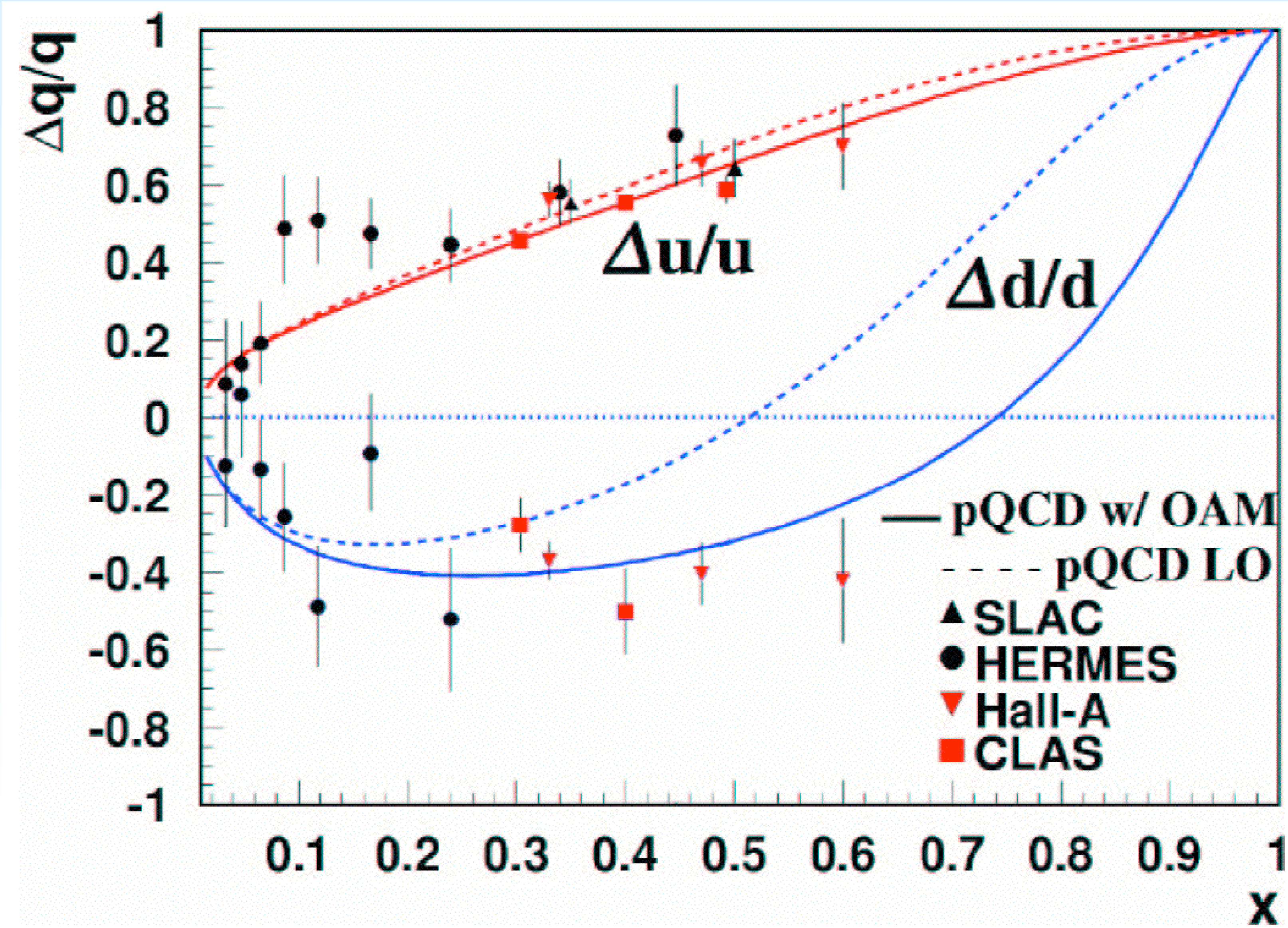
LO →

$$\frac{\Delta u}{u} \approx \frac{5g_1^p - 2g_1^d/(1-1.5\omega_D)}{5F_1^p - 2F_1^d}$$

$$\frac{\Delta d}{d} \approx \frac{8g_1^d/(1-1.5\omega_D) - 5g_1^p}{8F_1^d - 5F_1^p}$$

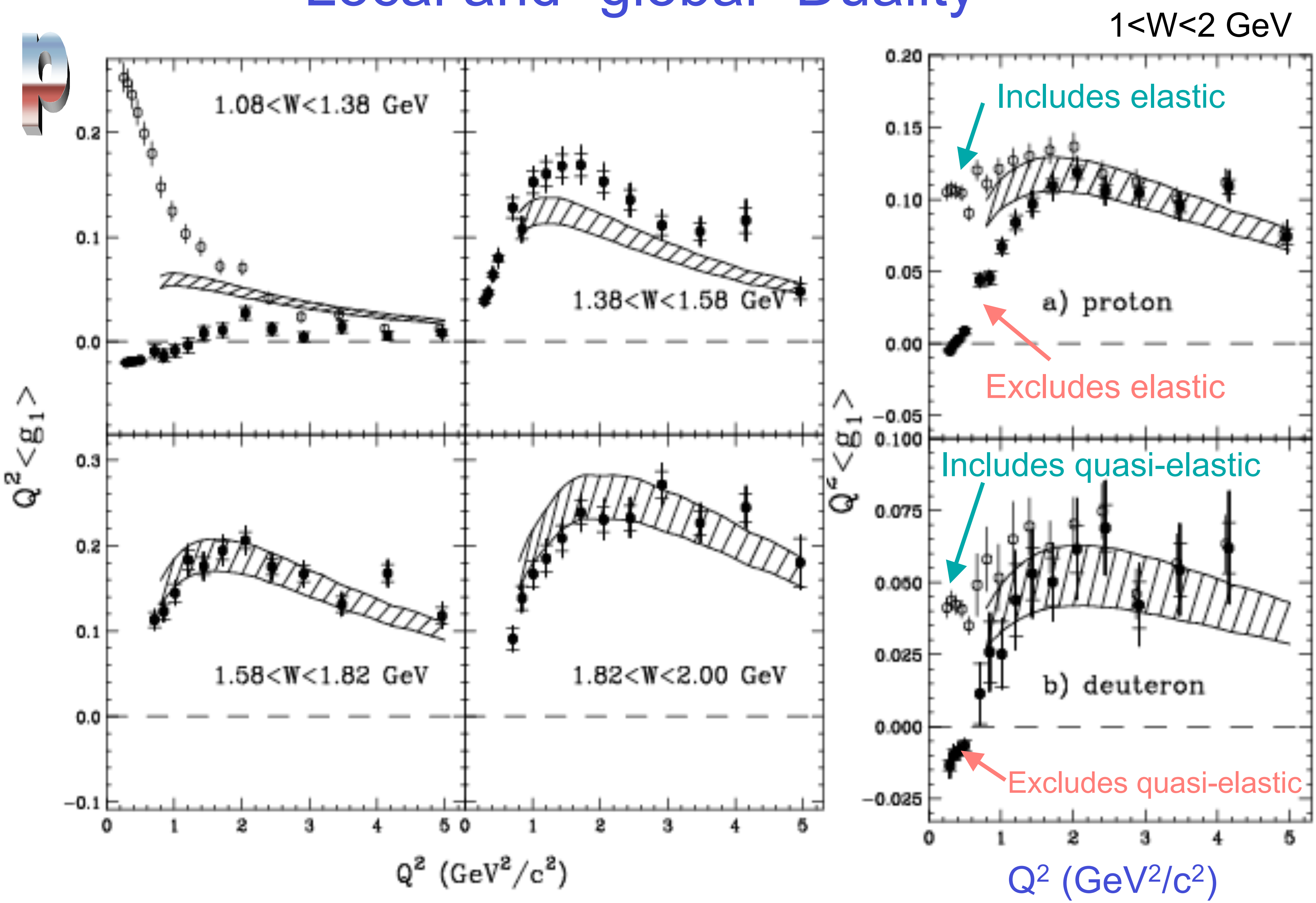
- CLAS data for $\Delta u/u$ are the statistically most precise available
- A_1^p or A_1^d are not very sensitive to $\Delta d/d$, but A_1^n is
- JLab Hall A and Hall B results for $\Delta d/d$ show no indication of a sign change
  - Disagree with simple pQCD predictions (assume hadron helicity conservation)

Orbital angular momentum may change this picture:

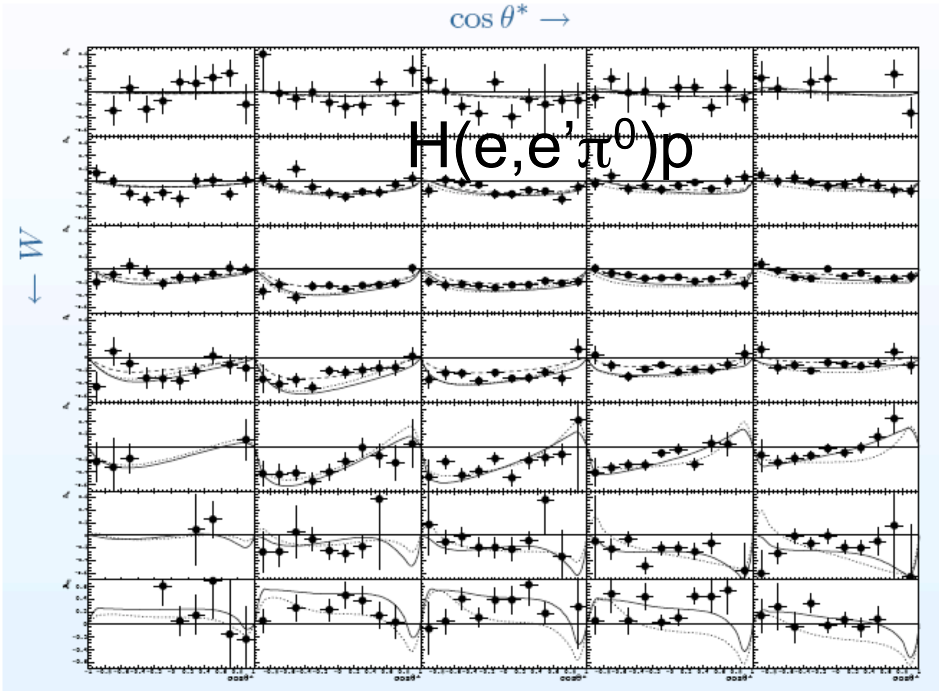


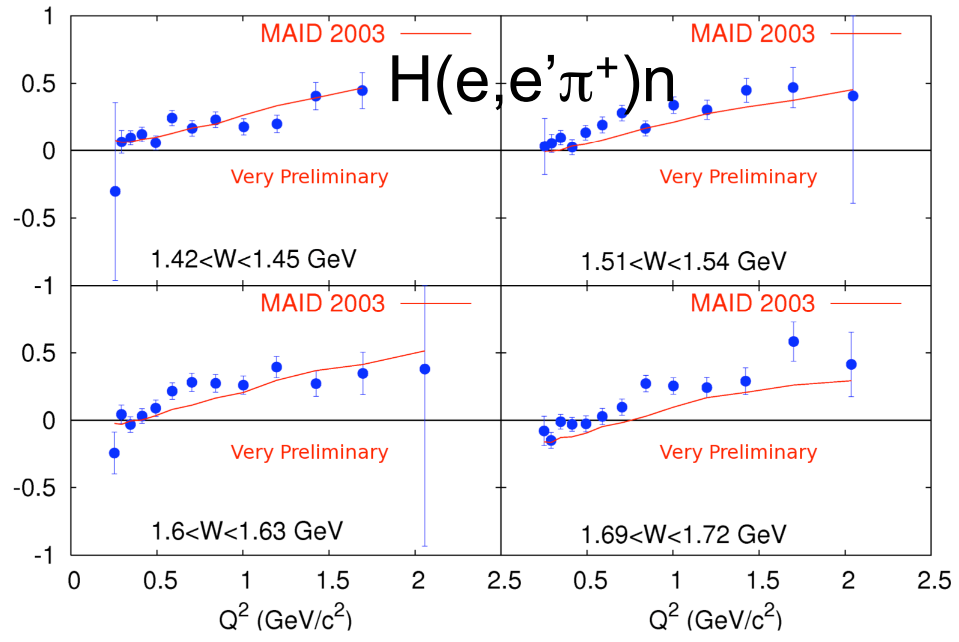
Avakian et al., Phys.Rev.Lett.99:082001,2007

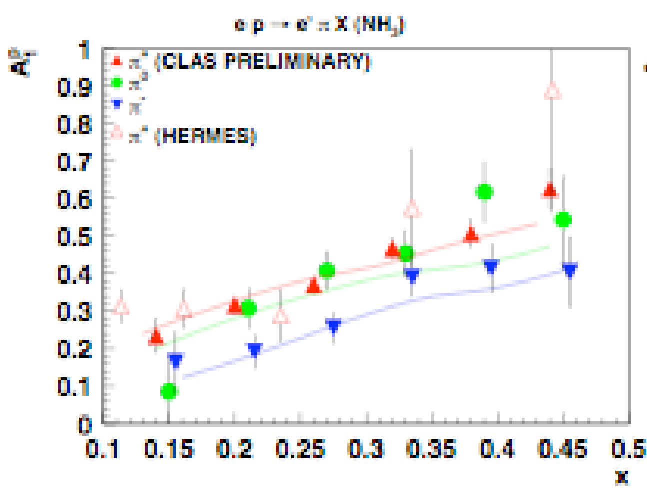
Local and "global" Duality

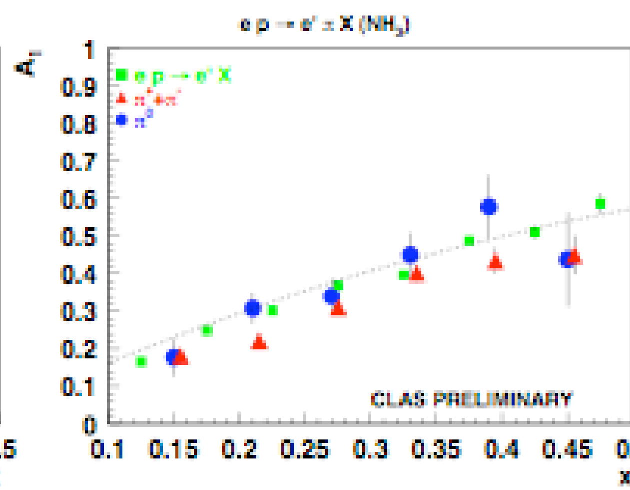


2-particle final states in CLAS





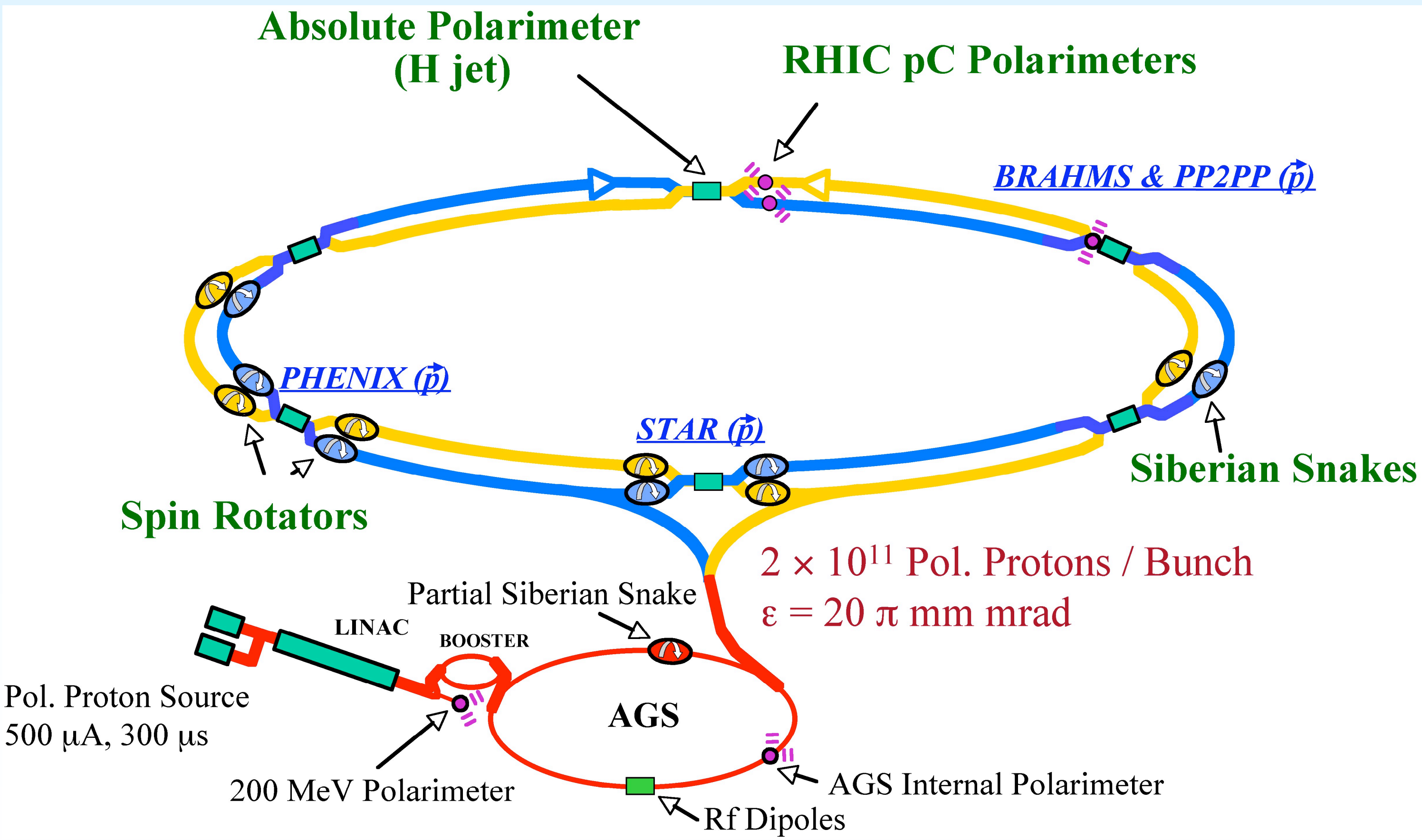




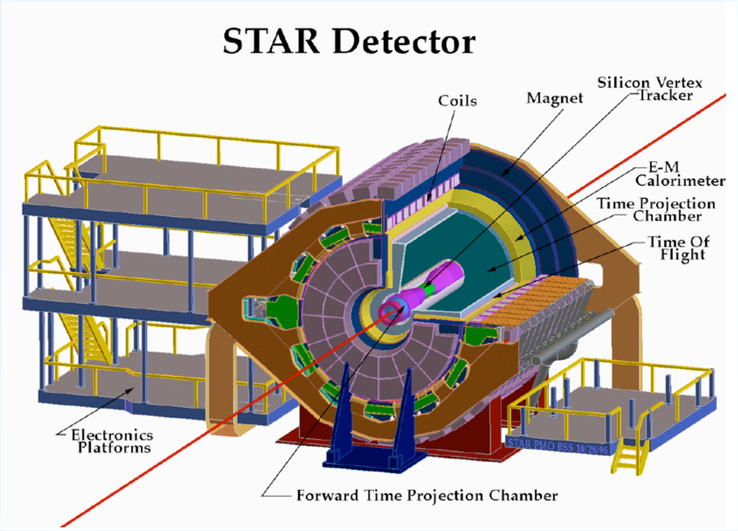
semi-inclusive DIS

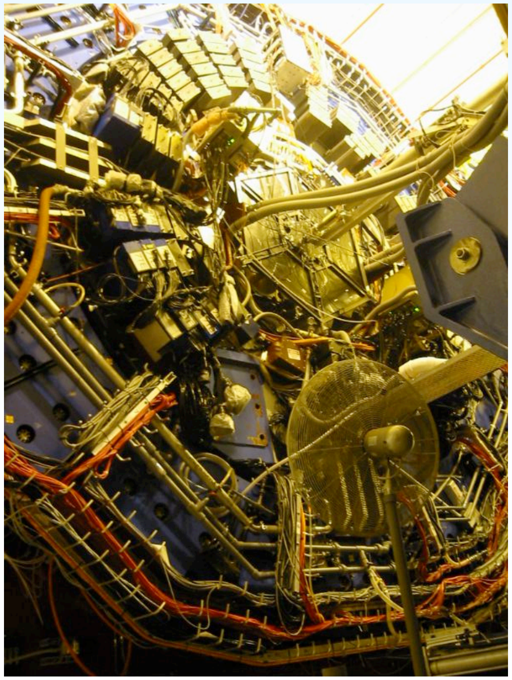
Spin Program at RHIC

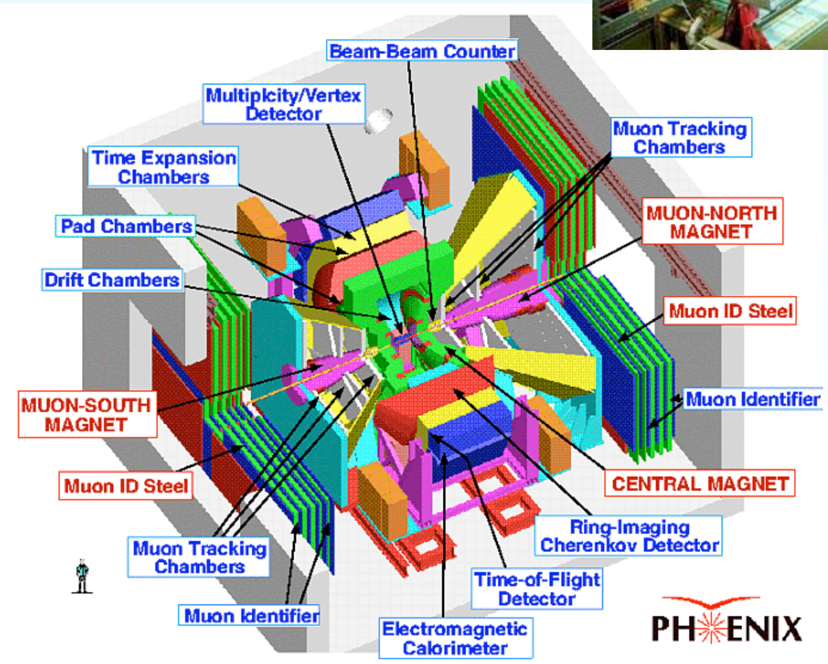
Proton-Proton collisions at $\sqrt{s}$ >200 GeV
qq, qg and gg elementary interactions

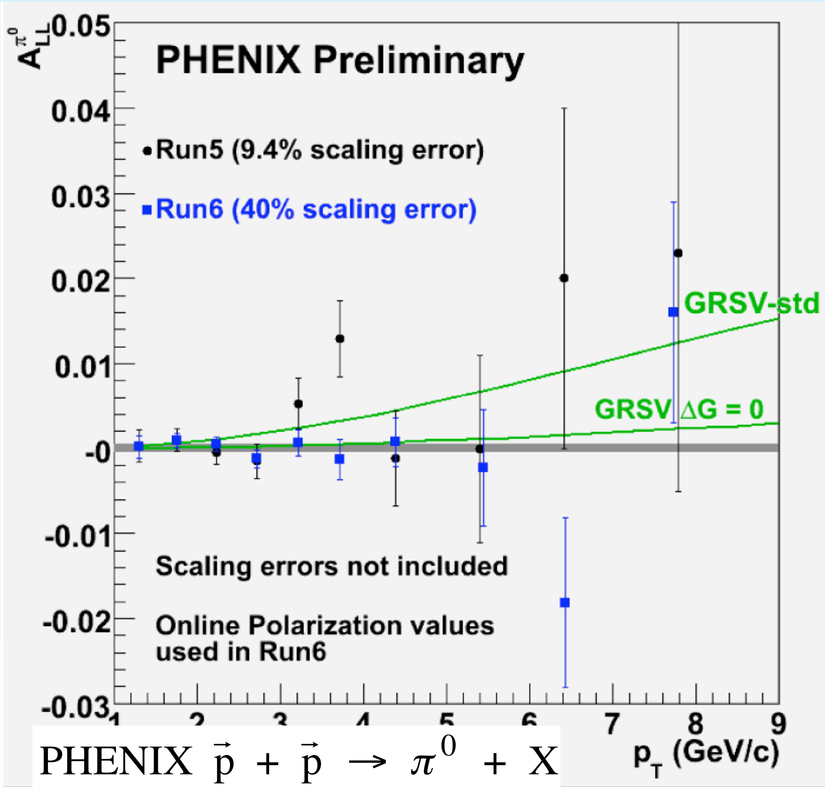


Experiments at RHIC: STAR and PHENIX

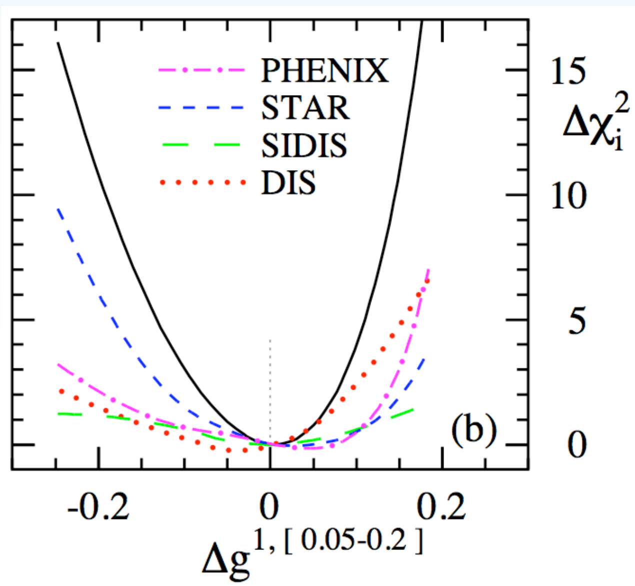


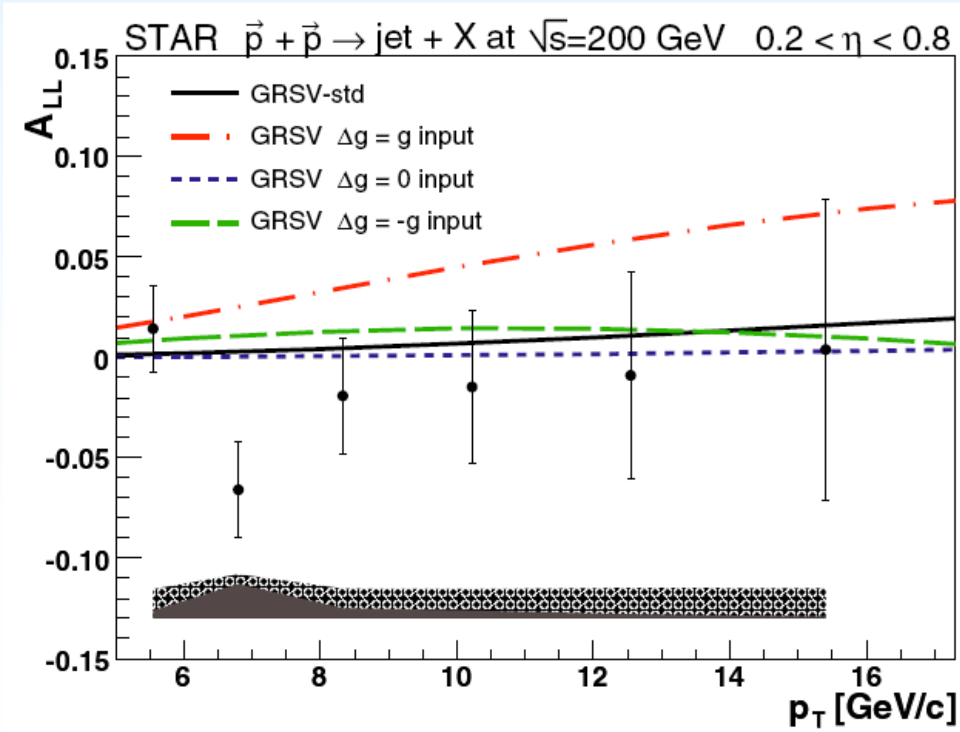






Preliminary Result:
ΔG appears small
in measured region



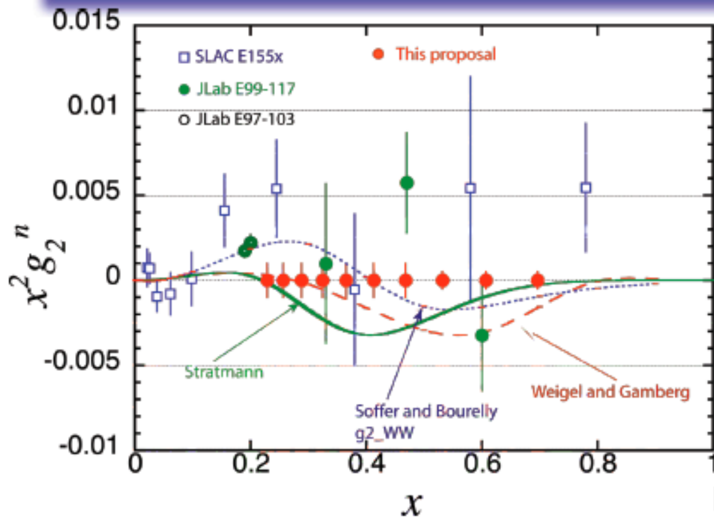


Outlook: The Future at JLab

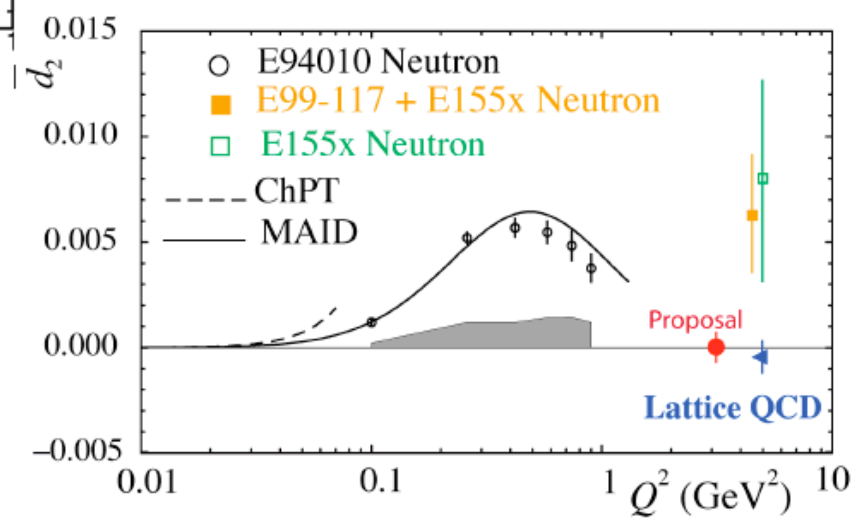
- Remaining experiments at 6 GeV
  - Hall A
    - E-06-010: Transverse target single spin asymmetry in $n\uparrow(e,e'\pi^-)$
    - E-06-011: Transverse target single spin asymmetry in $n\uparrow(e,e'\pi^+)$
    - E-06-014: Precision measurement of d_2 on the neutron
    - E-08-027: g_{2p} and δ_{LT}
  - Hall B
    - E-05-113: Semi-inclusive pion production (and DVCS) on $p\uparrow$
    - E-08-015: Semi-inclusive pion production (and DVCS) on $p\rightarrow$
  - Hall C
    - E-07-011: High precision g_{1d} in DIS region
    - E-07-003: SANE (SSFs on p, with emphasis on g_2)
- Approved experiments for 12 GeV
  - Hall A/C
    - E12-06-122: A_{1n} at high x with 8.8 GeV and 6.6 GeV beam in Hall A
    - E12-06-121: Precision measurement of g_2 and d_2 on the neutron
  - Hall B
    - E12-06-10: SSFs on longitudinal target with CLAS12
    - E12-07-107: Semi-inclusive pion production on $p\uparrow$

E-06-014: Precision measurement of d_2 on the neutron

Expected precision in Experiment E06-114

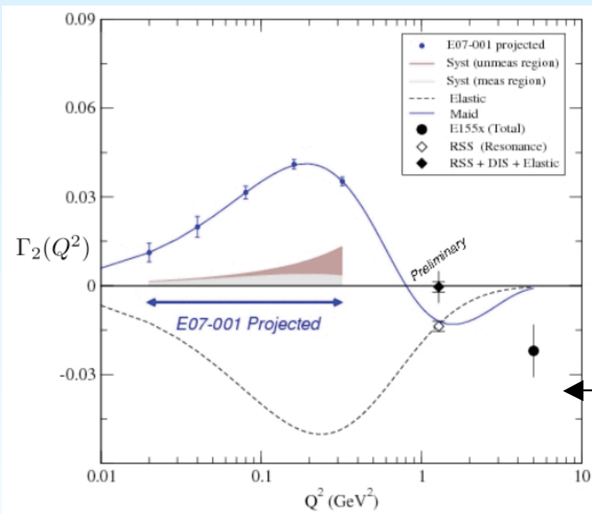


- At large Q^2, d_2 coincides with the reduced twist-3 matrix element of gluon and quark operators
- At low Q^2, d_2 is related to the spin polarizabilities



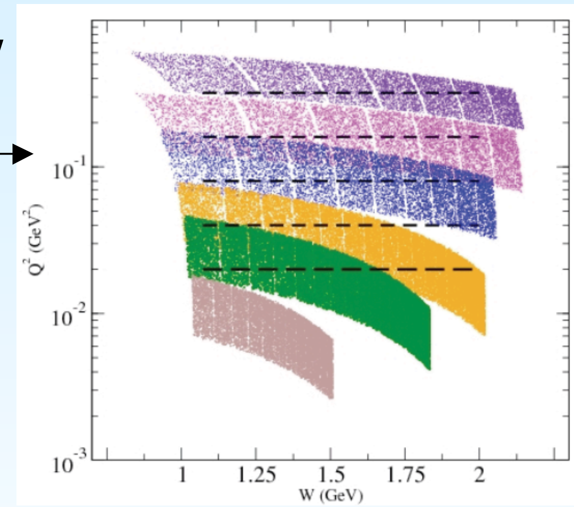
E-08-027
K. Slifer et al.

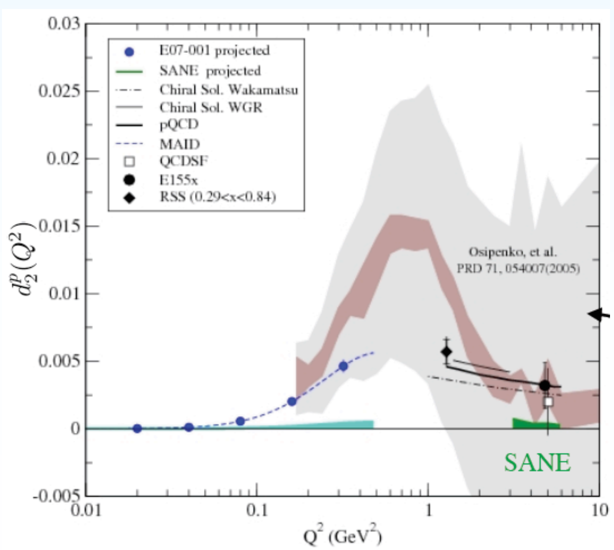
Low Q^2 Measurement of g_2^p and the δ_{LT} Spin Polarizability



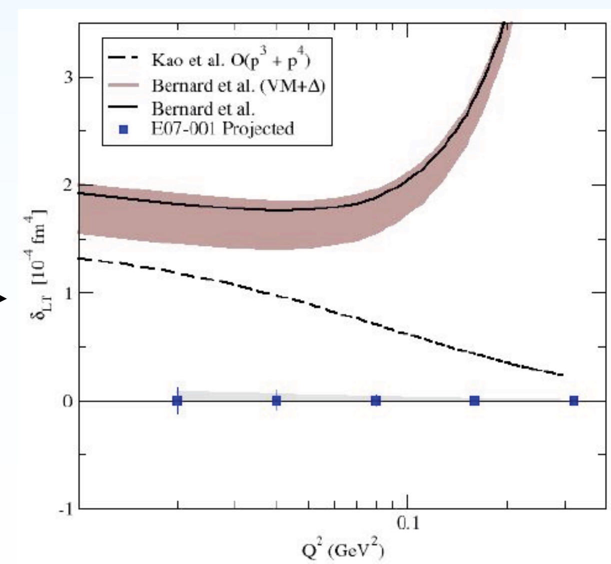
Check BCS at low Q^2

Measure g_2 at low Q^2 - will help EG4 (and EG1)



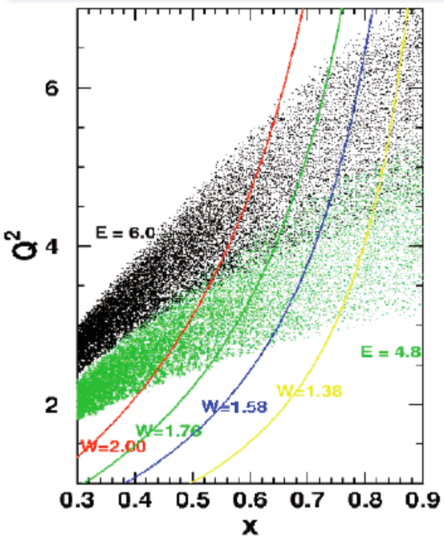


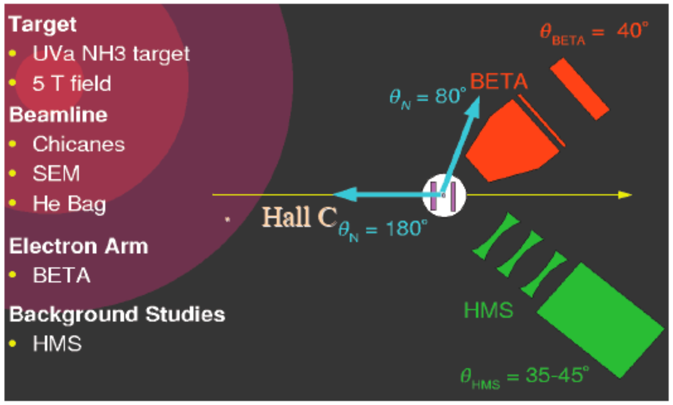
δ_{LT} tests χPT



E-07-003

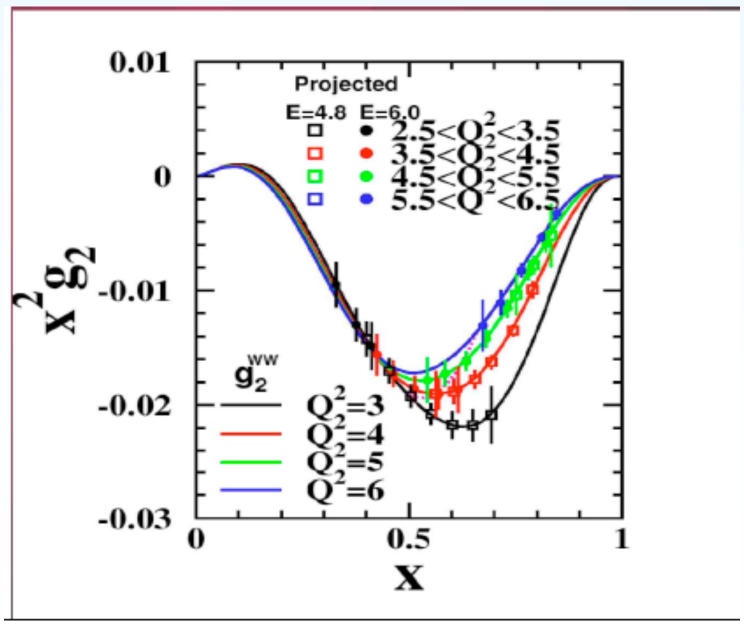
SANE experiment in Hall C

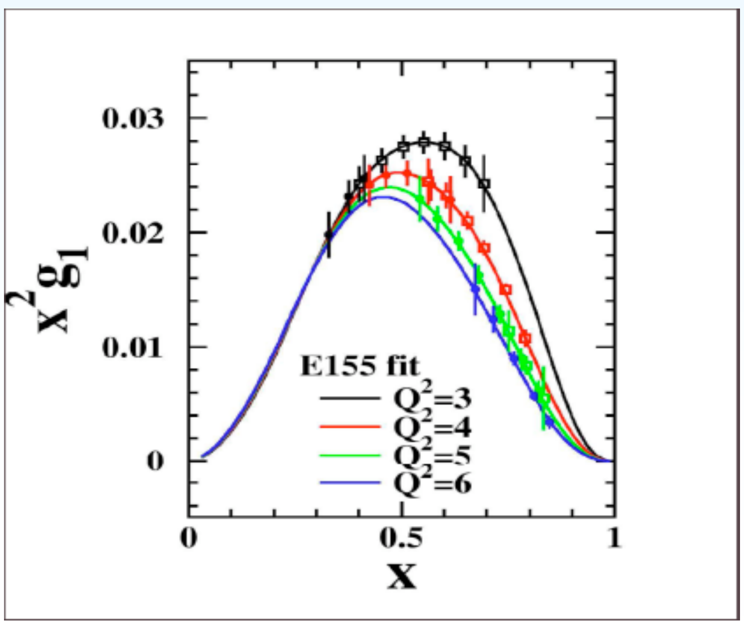




- Two beam energies:
  - 6 GeV (black)
  - 4.8 GeV (green)

- CEBAF polarized beam
  - 85 nA
  - 75% beam polarization

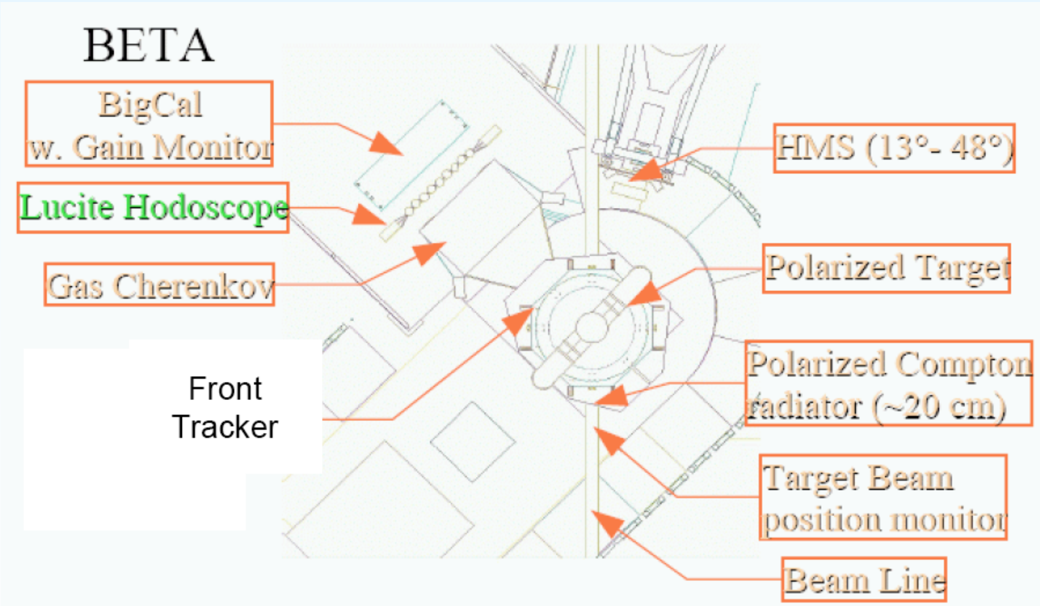


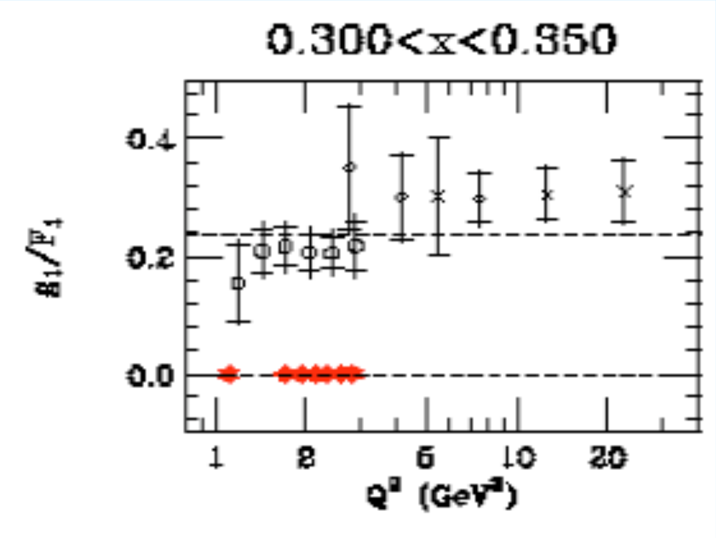


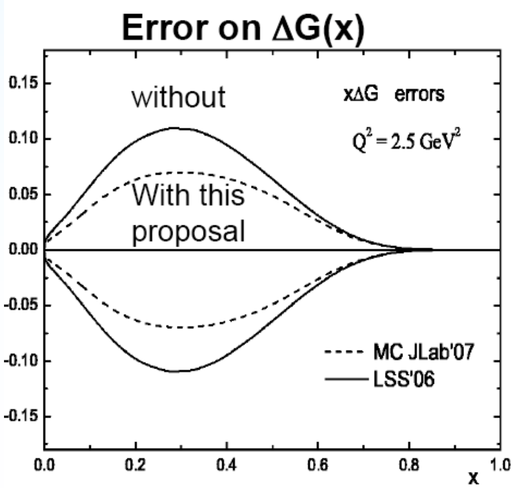
E-07-011
P. Bosted et al.

A High Precision Measurement of the Deuteron Spin-Structure Function Ratio g_1/F_1

8 days (in conjuction with SANE)

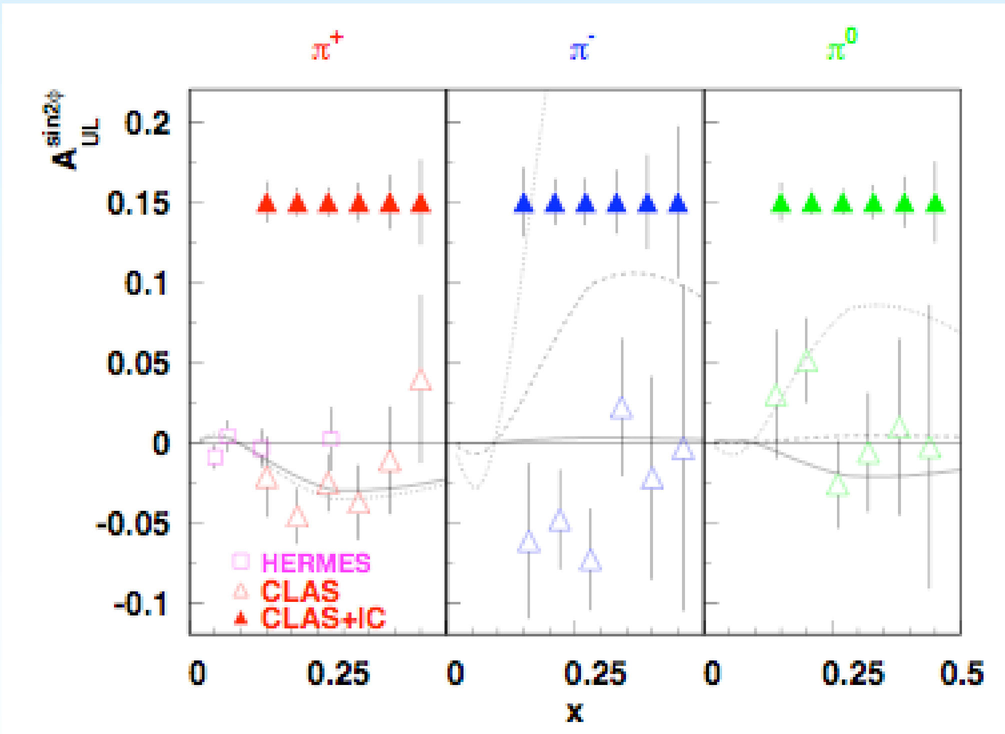






Future Experiments:
E-05-113 with CLAS and longitudinal target
Study semi-inclusive pion production, TMDs and Collins fragmentation function

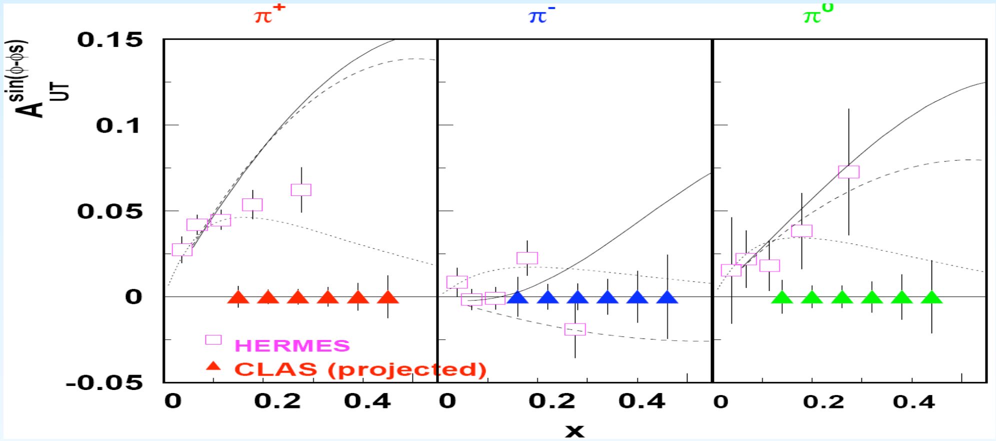
60 days (P_H=75%)

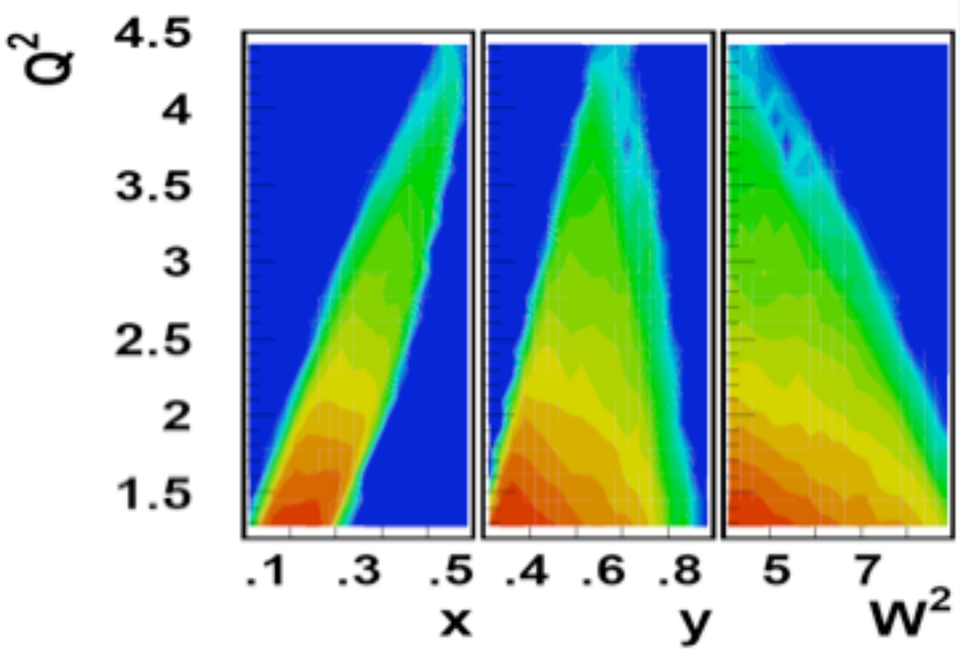


Expected Precision for sin2ϕ moment of target SSA

Existing CLAS data

E-08-015 with CLAS and transverse HD ice target
Study Spin-Orbit correlations in Semi-Inclusive DIS and Sivers distribution function



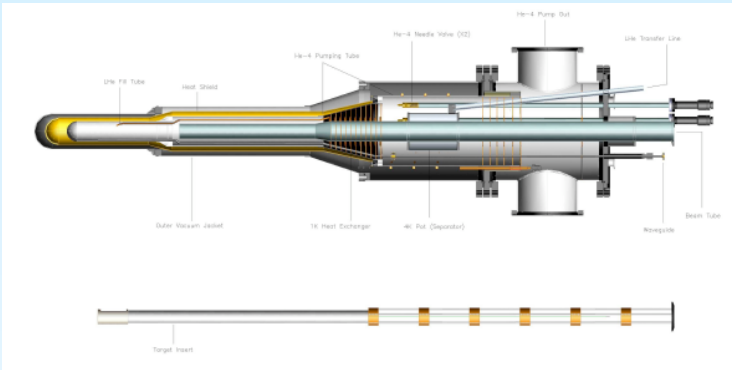


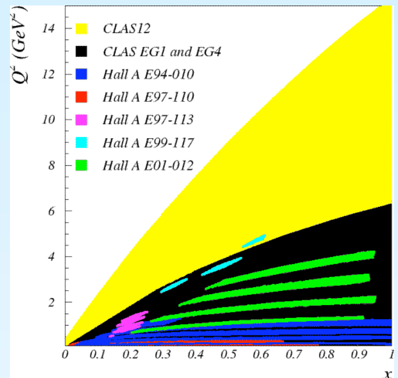
25 days (P_H=75% P_D=25%)

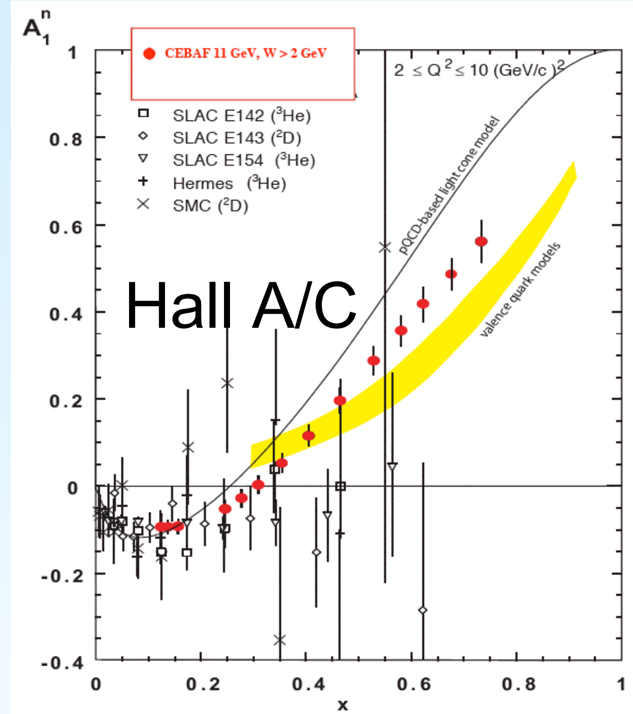
Potential to add to world data on g_2 and A_2

The Future with 12 GeV

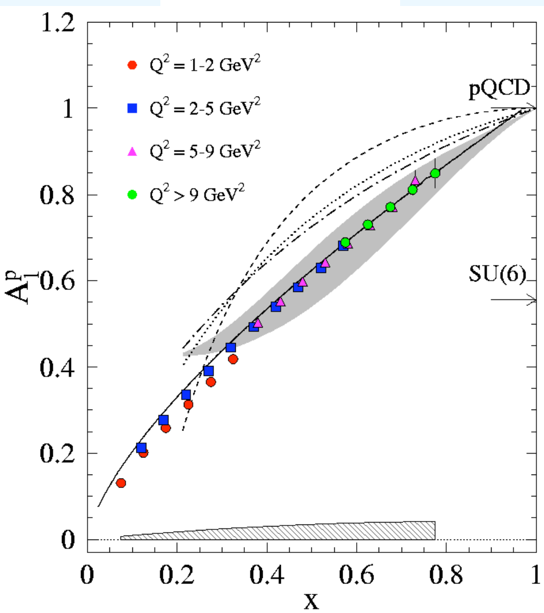
CLAS12

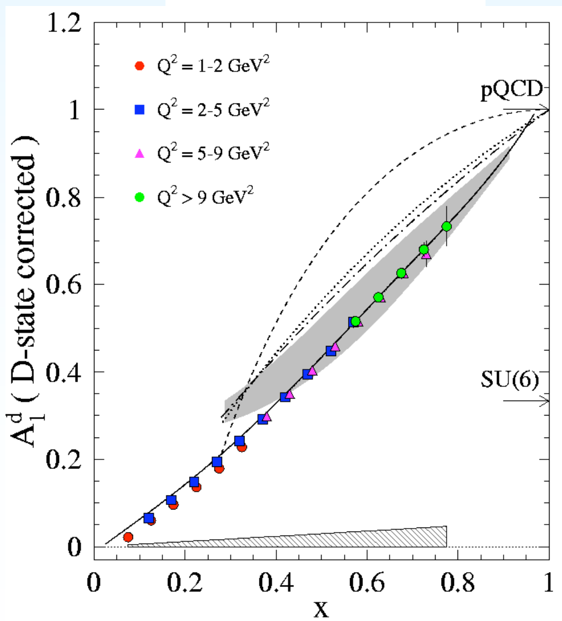


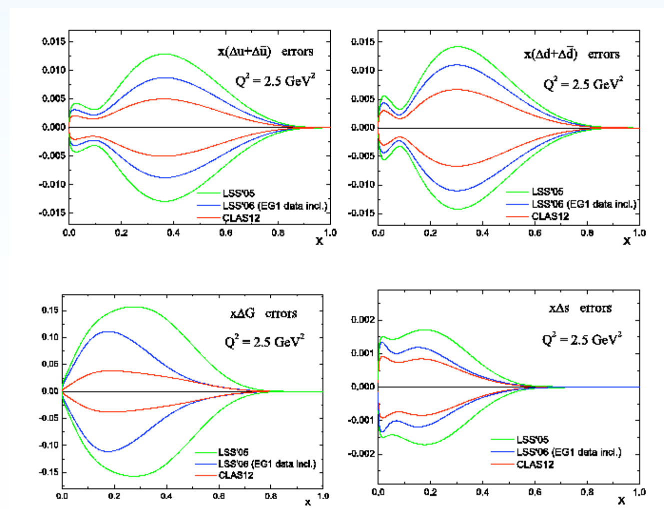




Proton W > 2; Q^2 > 1 Deuteron







Conclusions

- Nucleon Spin Structure has gotten very **rich!**
- Data from SLAC, CERN, HERA, MAMI, ELSA, LEGS, **JLab**, RHIC,…
- Sum rules, Moments, OPE, Duality, PDFs, Transversity, TMD PDFs, OAM, GPDs…
- Much to come: COMPASS+RHIC, Spring8, **JLab @ 12 GeV**, J-PARC, FAIR, … EIC?

The End